Deschutes River Mainstem Bank Erosion: 1991 to 2003

Prepared For:

Squaxin Island Tribe
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Prepared by:

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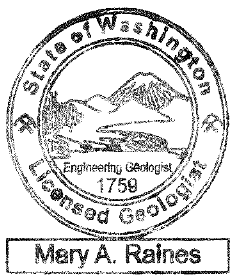

Mary A. Raines

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SUMMARY

Bank erosion along the mainstem of the Deschutes River, and particularly erosion of glacial terraces, is generally considered to be a major source of sediment to the river (Sullivan and others 1987, Moore and Anderson 1979, Collins 1994). For the purpose of supporting development of a TMDL for fine sediment, bank erosion along the mainstem Deschutes River was estimated for the time period from 1991 to 2003 and compared with bank erosion estimates for previous time periods of 1972 to 1981 and 1981 to 1991 (Collins 1994). Estimates of fine sediment from bank erosion are also compared with contributions from upland landslides and with estimates of fine sediment from surface erosion of unpaved roads in the basin.

Overall sediment yield from bank erosion for the period 1991 to 2003 where erosion area was measurable from aerial photographs is 745,000 yd^3 or 62,000 yd^3/year compared with a reported value of 870,000 yd^3 or 87,000 yd^3/year for the period 1981 to 1991 (Collins 1994). More sediment was generated from fewer sites in the earlier period that included a higher percent of large volume glacial terrace erosion sites. Erosion of the floodplain dominated bank erosion in the later period. For both time periods, bank erosion in general is concentrated in the upper and lower reaches of the mainstem and along reaches immediately upstream of natural and man-made channel constrictions.

Erosion volumes from hillslopes and glacial terraces in the Deschutes provide an estimate of the rate at which sediment enters the channel system, and is useful for comparing with other sources of sediment. Much of the sediment input is subsequently stored in the channel bed and floodplain for varying lengths of time. Estimates of floodplain bank erosion provide information on the changes in sediment storage useful in determining the rate of sediment export or net sediment yield from a watershed.

For the Deschutes River watershed, more than three times as much sediment is estimated from glacial terrace sources during the 1981 to 1991 period than from 1991 to 2003, during which time bank erosion predominantly involved floodplain deposits. Erosion from glacial terrace and hillslope sources, or the net sediment influx, is estimated for the 1991 to 2003 period at 101,000 yd^3 (8,400 yd^3/year) compared to 350,000 yd^3 (35,000 yd^3/year) in 1981 to 1991 (Collins 1994). The fine sediment fraction (< 2mm) of the net influx estimated from soil survey sieve data (Pringle 1990) is 59,000 yd^3 (4,900 yd^3/year) or approximately 58 percent for 1991 to 2003 and 280,000 yd^3 (28,000 yd^3/year) or 80 percent of the 1981 to 1991 total (Collins 1994). The difference in the estimate of percent fines between the two periods is accounted for in part from stabilization of eroding sandy glacial terraces in the lower watershed during the latter period. The estimated fine sediment fraction from all bank erosion sources (floodplains, glacial terraces, and hillslopes) between the two periods, however, was similar at 84 percent for 1991 to 2003 and 81 percent for 1981 to 1991.

The pattern of greater glacial terrace erosion in 1981 to 1991 may reflect erosion associated with the high magnitude storm of record in January 1990 included in this period. Floodplain erosion patterns in the mainstem during the 1991 to 2003 period may be more reflective of post-1990 storm sediment redistribution and/or channel behavior during higher frequency, lower magnitude discharge events. Armoring and stabilization of at least one eroding high glacial terrace in the

lower watershed may also contribute to the reduction of sediment in the later period. The result of updating bank erosion estimates for the Deschutes River suggests that sediment from glacial terrace sources is an episodic and variable source related to high magnitude storms, while erosion of the floodplain is less variable.

A modeling exercise was conducted to determine if surface erosion from an estimated 600 miles of unpaved, primarily forest roads in the basin is potentially a significant source of fine sediment and merits investigating in more detail. Results indicate sediment from unpaved roads to be as little as three percent of the total fine sediment influx sources to as much as 29 percent during some time periods and 9 percent overall. Landslides in the upper watershed contributed 23 percent of the estimated total fine sediment and 25 percent of the total sediment for a 31-year period. Erosion of glacial terraces contributed 68 percent of total fines and total sediment. The partial list of sediment sources quantified in this report accounts for the majority, 68 to 78 percent, of estimated sediment exiting the Deschutes River as defined by dredging and bathymetric records of Capitol Lake during the 31 years from 1972 to 2003.

ACKNOWLEDGMENTS

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1.0 INTRODUCTION

1.1 Purpose and Scope of Report

This report focuses primarily on updating and integrating previous work on mainstem Deschutes River bank erosion conducted by McNicholas (1984), Cramer (1997), and specifically Collins (1994). Collins (1994) quantified bank erosion for two time periods with an emphasis on understanding the locations and causes of channel bed aggradation and channel movement. The Collins report (1994) cites a number of potential management and planning applications for that study, particularly those associated with coarse sediment introduction and bedload movement. This report has a more focused application specific to understanding sources of fine sediment to support development of a sediment TMDL for the Deschutes River.

To put fine sediment from bank erosion sources into perspective, also included in this work is a partial sediment budget comparing estimates of fine sediment from landslides and unpaved roads with bank erosion sources. Basin sediment output was estimated from dredging and bathymetry studies of Capitol Lake. A more comprehensive analysis of fine sediment and source areas is possible pending completion of a water quality data synthesis in progress by the Weyerhaeuser Company, a major landowner in the upper basin.

1.2 Organization of This Report

Introductory and physical setting material is provided in Sections 1 and 2. Section 3 contains a summary of references and documents relevant to this work. Bank erosion methods and results are found in Section 4 along with a comparison and discussion of bank erosion from earlier periods. Section 5 contains a summary and discussion of sediment from other sources, specifically landslide and road erosion estimates. A comparison of sediment sources along with a rough sediment budget for the Deschutes River watershed is found in Section 6, and Section 7 provides a discussion and conclusions to be drawn from this work. A short section relating to methods for future updates of bank erosion has been included in Section 8, followed by references in Section 9. Five appendices contain the data for bank erosion sites for the 1991 to 2003 period, an index and maps of erosion sites on shaded relief images showing valley and floodplain features, the landslide inventory, details on the road erosion modeling exercise, and inventoried erosion sites within the delineated floodplain.

2.0 Physical Setting of the Deschutes River Basin

The Deschutes River is located at the southern end of Puget Sound in western Washington (Figure 1). It originates in the forested foothills of the western Cascade Mountains then flows generally northwest through farm, rural, and suburban communities of the southern Puget Lowland to its mouth at man-made Capitol Lake, a former intertidal estuary (Williams et al. 1975) located below the state capitol campus in Olympia. Total relief in the basin is 3,870 feet (1,180 m), also the height of the highest point at Cougar Mountain. The 163 mi^2 watershed is 35 miles in length, giving it an average width of 4.7 miles and a long, narrow configuration. Prior

Figure 1. Location of Deschutes River in Southwestern Washington.

to settlement, the area was covered in forests interspersed with natural prairies (Glassey et al. 1958).

2.1 Geology of the Deschutes River Basin

The headwaters and southern flank of the Deschutes River watershed originate in Tertiary-aged[1] primarily volcanic rocks of the southern Cascade Range (Figure 2). These include andesite, basalt, and flow breccias of the Northcraft Formation and siltstones and sandstones of the underlying McIntosh and overlying Skokumchuck Formations (Noble and Wallace 1966). A similarly-aged intrusive rock or dike just downstream of Deschutes Falls at river mile 41 is thought to have forced the sharp bend in the river at that location and held the falls in place for some time (Noble and Wallace 1966). Deschutes Falls defines the upper watershed and blocks fish passage (Williams et al. 1975). Approximately two miles from its mouth the Deschutes River flows over Tumwater Falls, a series of falls in Crescent Formation basalt (Walsh et al. 2003) laddered for fish passage in 1954 (Williams et al. 1975). Bank erosion along the river between these two falls is the main subject of this report.

The area between the two falls is primarily a gently sloping glacial plain consisting largely of unconsolidated sand, gravel, and clay reflecting a complicated history of Pleistocene glacial advance and retreat. The glacial drift plain in the study area consists of many glacial landforms – terminal and recessional moraines, ground moraines, outwash channels, drumlins, kettle lakes, and undrained depressions (Glassey et al. 1958). Elevations in the glacial plain are rarely higher than 600 or 700 feet (200 m). In contrast, the slopes between the upper headwaters scoured by small alpine glaciers and the lowlands below have been largely untouched by glaciers; consequently, the bedrock underlying most of the upland in the basin is deeply weathered in place (Thorsen and Othberg 1978, Pringle 1990). The higher elevations of the weathered terrain are gently sloped above nick points defining steeper valleys incised in the older surface. Thorsen and Othberg (1978) suggest the valley incision may still be an active erosion process.

The Deschutes River and the surrounding area mark the southern extent of continental glaciation in the Puget Sound. Glacial meltwater from the Vashon ice sheet drained southwest through several routes in the study area into the Chehalis River drainage (Noble and Wallace 1966). As the ice receded and exposed the sub-glacially carved troughs of Eld and Budd Inlets, drainage subsequently reorganized to flow northward through the outwash plain between and on top of blocks of ice, forming interconnected lakes and depositing prograding sandy sediments (Booth 1994 in Palmer et al. 1999 and Walsh et al. 2003). These sands and silts are informally named the Tumwater sand by Walsh et al. (2003) and are widespread throughout the south Sound area, specifically within the lower 15 miles of the Deschutes River. Streams draining to Puget Sound after deglaciation were able to cut deep channels in this fill that were subsequently filled as sea level rose to its present-day level.

[1] roughly 10 to 50 million years old

Figure 2. Generalized geology of the Deschutes River basin.

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2.2 Geologic and Geomorphic Influences on Bank Erosion

The Deschutes River within the study area is easily partitioned into three areas of similar, if not uniform morphology (Figure 3). Sullivan et al. (1987), Pringle (1990), and Collins (1994) also divide the area into three somewhat similar zones. Each exerts a different influence on modern erosion processes.

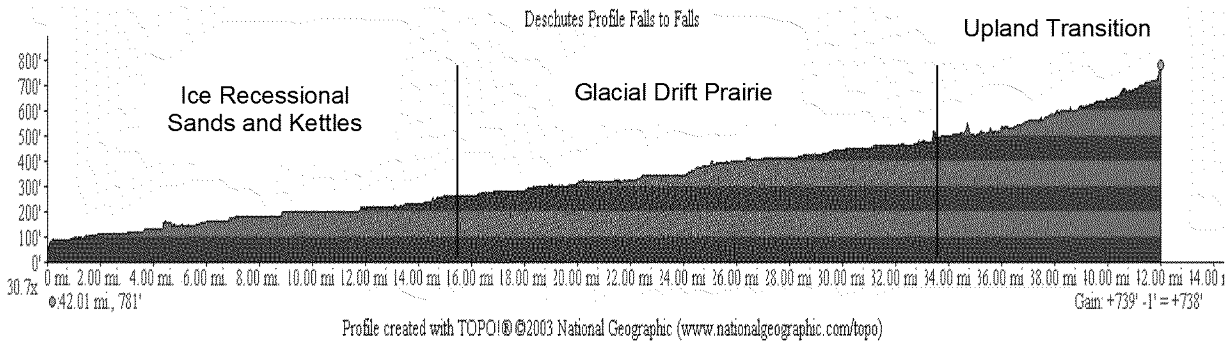

Figure 3. Longitudinal profile of the mainstem Deschutes River to Deschutes Falls at RM 42 showing three broad geomorphic areas (approximate vertical exaggeration of x50).

The upper portion of the study area between Deschutes Falls and approximately river mile 34 defines an area of transition between the upland forested headwaters and the glacial plain. Land use in this area is primarily commercial forestry with a small amount of rural development around the river corridor (Figure 4). The mainstem river gradient is steepest here with an average slope of 0.0054 measured from Cramer (1997) thalweg distance and elevations from a LiDAR digital elevation model (DEM), but declines throughout the reach causing sediment deposition and subsequent lateral channel movement and floodplain and terrace erosion. Glacial meltwater flowed into the Deschutes drainage from the north between Bald Hill and Clear Lakes and the Toboton Creek divide. The remaining high-gradient tributaries join with the mainstem from the south through this section of river, adding to the sediment load and streamflow. The Deschutes and its tributaries downstream of the falls have incised into portions of the glacial terraces; upstream of the falls this downcutting is not as pronounced (Thorsen and Othberg 1978). Valley confinement alternates between high glacial terraces mantling mountain hillslopes, and floodplain width is variable.

In the middle portion of the study area from approximately river miles 34 to 16, the Deschutes River flows through the gently sloping glacial drift plain or "prairie." This area was covered by glacial meltwater during the receding stages of the Vashon ice sheet. The Deschutes River occupies a former glacial outwash channel and is somewhat entrenched throughout the Ruth Prairie area where it flows against the upland flank at the southern extent of the drift plain. Average channel slope throughout this area is 0.0024. Stream banks are generally between 5 and

10 feet above average flow depths, and are composed primarily of modern floodplain deposits

Figure 4. Mainstem Deschutes River within the study area and Thurston County land use zoning.

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(Pringle 1990). Few significant tributaries join the river in this area, and those that do have wetlands and low gradient reaches where most sediment is deposited. Land use here is primarily agriculture with some forestry and rural housing (Figure 4).

The lower 16 miles of the Deschutes River occupies a post-glacial channel cut largely through Vashon recessional sands, also called the Tumwater sand by Walsh et al. (2003). The modern valley here formed through erosion of the recessional sediments to an elevation determined by the bedrock outcrop at Tumwater Falls (Palmer et al. 1999). This area of the river is defined by a lower average slope of 0.0020, a wider floodplain, and an average higher sinuosity than is found in the upstream areas. Both the lower gradient and erodibility of the sandy glacial terraces have enabled the stream to create a wide floodplain. In the area surrounding the river are numerous kettles and kettle-lakes formed when isolated blocks of stagnant ice were buried in the sediment from the melting glacier. The irregular terrain contributes to a lack of organized drainage; consequently, few tributaries drain to the Deschutes River in this area. The only significant tributary is Spurgeon Creek, itself occupying a former outwash channel (Noble and Wallace 1966). Land use in this area is increasingly suburban downstream (Figure 4).

3.0 Previous Related Work on the Deschutes River

A number of studies have been conducted on aspects of erosion and flooding in the Deschutes River in the last 25+ years. The reason for much of this work initially appears related to sediment filling of Capitol Lake and establishing liability for dredging, and later in support of river and land management planning. Several studies conclude that erosion of glacial terraces and stream banks along the mainstem dominates sediment production in the Deschutes River (Moore and Anderson 1979, McNicholas 1984, Sullivan and others 1987, Collins 1994). Summarized below are those reports related to quantifying sediment sources used in this report.

Nelson (1974) estimated annual suspended sediment discharge in the Deschutes and Nisqually Rivers as part of a Department of Ecology program. Annual suspended sediment discharge in the Deschutes River was estimated at 25,000 tons (30,000 yd^3) based on the relation of instantaneous suspended sediment concentration to discharge from samples periodically collected at three sites during November 1971 to June 1973. Nelson found the majority of suspended sediment to originate in the upper basin: 22,000 tons or 88 percent of the total sediment discharge was estimated from the site near La Grande (station 12078902) at approximately river mile 38, and 24,000 tons or 96 percent of the total sediment discharge was estimated at the gaging station just downstream of Vail at approximately river mile 26. Mitchell Creek, a major tributary joining the mainstem just upstream of the La Grande station, produced the highest measured sediment concentration during the sample period out of 15 sites in the Deschutes and Nisqually River basins. Nelson concludes that the largest changes in sediment transport resulting from logging and road construction in the two basins was occurring in the upper Deschutes River due to the prevalence of fine soils.

Moore and Anderson (1979) reported on sediment monitoring conducted by the Washington Department of Ecology for the purpose of understanding sources of sediment to Capitol Lake. Suspended sediment was measured at 13 locations from Vail upstream and near the mouths of major tributaries during November and December of 1977 when most of the annual sediment load was assumed to be transported. During this two month interval, 11 monitored tributaries contributed 25 percent (3,043 tons) of the total suspended sediment measured at Vail on the mainstem Deschutes (12,233 tons), and 18,262 tons were calculated at the mouth of the Deschutes. The authors conclude that the balance of suspended sediment between the tributaries and Vail had to originate from the stream bed or banks of the Deschutes mainstem. For a period beginning from either January or April 15, 1977 to January 10, 1978, two out of at least 12 known large and actively eroding mainstem banks were also monitored for erosion.

The purpose of the McNicholas' 1984 work was to identify and quantify sources of sediment filling Capitol Lake and to develop a management plan for treating the sediment source sites. Forty miles of the Deschutes River above Tumwater Falls were surveyed, and field estimates for the volume and soil composition of bank erosion were made (length, height, annual lateral recession), with lateral recession estimates verified from 1972 and 1981 aerial photographs. Annual erosion from stream banks was estimated at 34,791 yd^3; 78 percent as fine sand, silt, and clay and 22 percent coarse material. Surveys of forest and agricultural lands were also conducted. Aerial photographs were used to assess vegetative cover in the forest lands, and six or eight farms adjacent to the Deschutes River were surveyed to assess the impact of cattle to stream banks and riparian vegetation. The methods used for assessing stream conditions, conducting a landslide investigation in the forest land, and evaluating erosion control measures on forest roads are not specified in the report. McNicholas (1984) concludes that sediment directly attributable to on-site logging and streamside cattle grazing were not significantly contributing to sedimentation of Capitol Lake, although some water quality problems from farming were identified. From lake sediment analysis and hydrologic modeling, McNicholas further concludes that 60 percent of Capital Lake sediments are of stream bank origin and 14 percent of stream banks are eroding primarily associated with an increase in overall streamflow associated largely with extensive clearcut logging in the upper watershed. Since most of the watershed had been cut over, it was assumed that stream discharge would begin to decrease and the river would regain stability as the forest cover matures.

In response to concerns of sediment and flooding, the Weyerhaeuser Company developed a watershed management plan in 1974 for their ownership in the upper Deschutes River (Sullivan et al. 1987). The plan included guidelines to reduce environmental risks in each of the major tributaries. A water quality monitoring plan was implemented in 1975 consisting of suspended sediment concentration and turbidity measurements at one location in the mainstem and three headwater streams. In addition to water quality monitoring, Weyerhaeuser scientists have also authored or supported a number of fish habitat and ecological studies in the headwaters.

Sullivan et al. (1987) compiled internal Weyerhaeuser Company reports and data from 1975 to 1987 and discussed the effects of forest management on water quality and fisheries. Among their many results and discussions are the following. In ten years of daily sediment sampling they found little difference between the annual suspended sediment yield in tonnes/km^2 at the 1000 Road on the mainstem and at Tumwater, which they attribute to greater sediment concentrations and lower runoff rates in the downstream direction. From suspended sediment measurements at three locations taken during storms occurring in 1977 to 1978, they found a linear increase in sediment concentration downstream, results inconsistent with the suspended sediment rating curves developed by Nelson (1974). A general relationship was found between log haul road use and increased turbidity in tributaries with differences due to the amount of road drainage to streams, geology, and precipitation from year to year. During the 12-year monitoring period, landslides were estimated to contribute approximately 40,000 tonnes (44,000 tons), half attributable to roads. They conclude, based primarily on Moore and Anderson's 1979 work, that the majority of sediment deposited in Capital Lake is from erosion of glacial deposits along the mainstem and lower tributaries.

The primary focus of Collins (1994) report was on understanding the sources of coarse sediment and the processes contributing to bank erosion along the mainstem of the Deschutes from Tumwater Falls at river mile 2 to Deschutes Falls at river mile 41. Bank erosion locations were identified from aerial photographs for every decade from 1941 to 1991, and erosion volumes were calculated for the 1972 to 1981 and the 1981 to 1991 intervals. Collins duplicated the work of McNicholas (1984), and notes unexplainable discrepancies in the location, number, and measurement of bank erosion sites between the two efforts. Collins reported a larger number of eroding sites for the same period and a correspondingly higher volume of bank erosion. The volume of sediment from significant landslides delivering directly to the mainstem Deschutes River was also estimated from previous landslide inventories conducted by the Weyerhaeuser Company and Toth (1991). Sediment volume contributions from tributary bank erosion and tributary-deposited landslides were broadly characterized, while quantification of mainstem bank erosion sites and volumes is based on aerial photographic analysis and field verification of a large portion of the mainstem. Erosion from the many miles of forest roads was not evaluated, presumably because the focus of this study was on understanding coarse sediment sources. Incidents of bank erosion and channel migration over the photograph record are correlated in the Collins study.

4.0 MAINSTEM DESCHUTES RIVER BANK EROSION

4.1 Methods

As recommended by Collins (1994), bank erosion sites were first identified and mapped by comparing sequential aerial photographs that spanned the interval from 1991 to 2003, and then a sample was field checked. Collins (1994) found the photo-based approach more reliable for identifying sites with significant erosion, and field inventories more reliable for identifying less extensive and more recent sites of erosion. Only those erosion sites measurable from aerial photographs are included in bank erosion volume estimates in both surveys. Bank erosion sites inventoried from the 2003 photos were also correlated with sites inventoried by Collins where they coincided.

This work differs from the 1994 work in that digital orthophotos and LiDAR images of the river and surrounding valley were available and used at a larger scale to map the eroded areas, which were then digitized into GIS. The volume of bank erosion at each site was calculated from GIS-calculated areas and bank heights from May 2005 field measurements, field work from the previous studies (McNicholas 1984; Collins 1994) where those applied, or extrapolated based on adjacent measurements on the same surface. Particle size estimates were made from sieve data for associated soil units in the Thurston County Soil Survey (Pringle 1990).

The original 1991 orthophotographs used in the Collins work were not available, and several photographic sources of 1990 photos were used in place of them. Since the available 1990 photos were taken after the January 1990 flood of record, they correlated well with river conditions visible in the 1991 photos used by Collins. Black and white stereo aerial photography flown in 1990 borrowed from the Weyerhaeuser Company covered the upper watershed to site 320 (Appendix B). Black and white NRCS 1990 orthophotographs were available for the lower watershed; however, there was a gap between the NRCS 1990 and the Weyerhaeuser photos between sites 320 and 410 where only the 1990 digital orthophotographs were available. Aerial photography for 2003 viewed in stereo was used to identify new bank erosion sites since the Collins work.

Stereo and orthophotographic comparisons were supplemented with digital orthophotographs for 1990/1991/1994 and with third return (bare earth) LiDAR images from a 2002 flight of the Deschutes. The LiDAR was superimposed on 1990/1991/1994 and 2003 digital photography to aid in identifying differences in floodplain and terrace features. Areas of erosion were mapped on 1:5,000 scale printouts of the 1990/1991/1994 digital orthophotographs where the area subsequently eroded could be best defined (Figure 5). The photographs were examined for evidence of channel shifting, visible bank erosion, and missing canopy using landmarks and individual tree canopies as reference where possible. As the 1990 and 2003 digital orthophotographs were of different projections, they could not be overlaid directly in the ArcMap© software. However, the LiDAR hillshade image could be projected onto both sets of digital orthophotographs, and this greatly facilitated identification of eroded areas (Figure 6). Generally, there is good alignment in channel and floodplain features between the 2003 digital orthophotographs and the LiDAR. Side channels cut through under a canopy are only visible in the stereo photographs in certain lighting conditions. Water elevation is different between the 1990 and 2003 photographs, and some bars are exposed in 2003 that are not visible in 1990.

Bank heights were measured just above water surface but below bankfull depth due to the difficulty in determining bankfull height at many sites. A possibility exists that the eroded surface mapped at some sites was a lower surface completely eroded up to a higher elevation surface, making height of the eroded area hard to validate in the field.

The 2003 erosion sites were also correlated to Collins (1994) and Cramer (1997) reach numbers (Appendix A). Collins used McNicholas' (1984) segments which are based on homogenous physical characteristics and range in length from ¼ to 3 miles. Although of unequal length, there are 42 segments coincidentally similar in number to reported river miles. Cramer reaches are also intentionally not uniform in length but are more numerous.

Figure 5. 1990 digital orthophotograph of a portion of the Deschutes River. Labeled polygons (yellow) are those areas subsequently eroded by 2003.

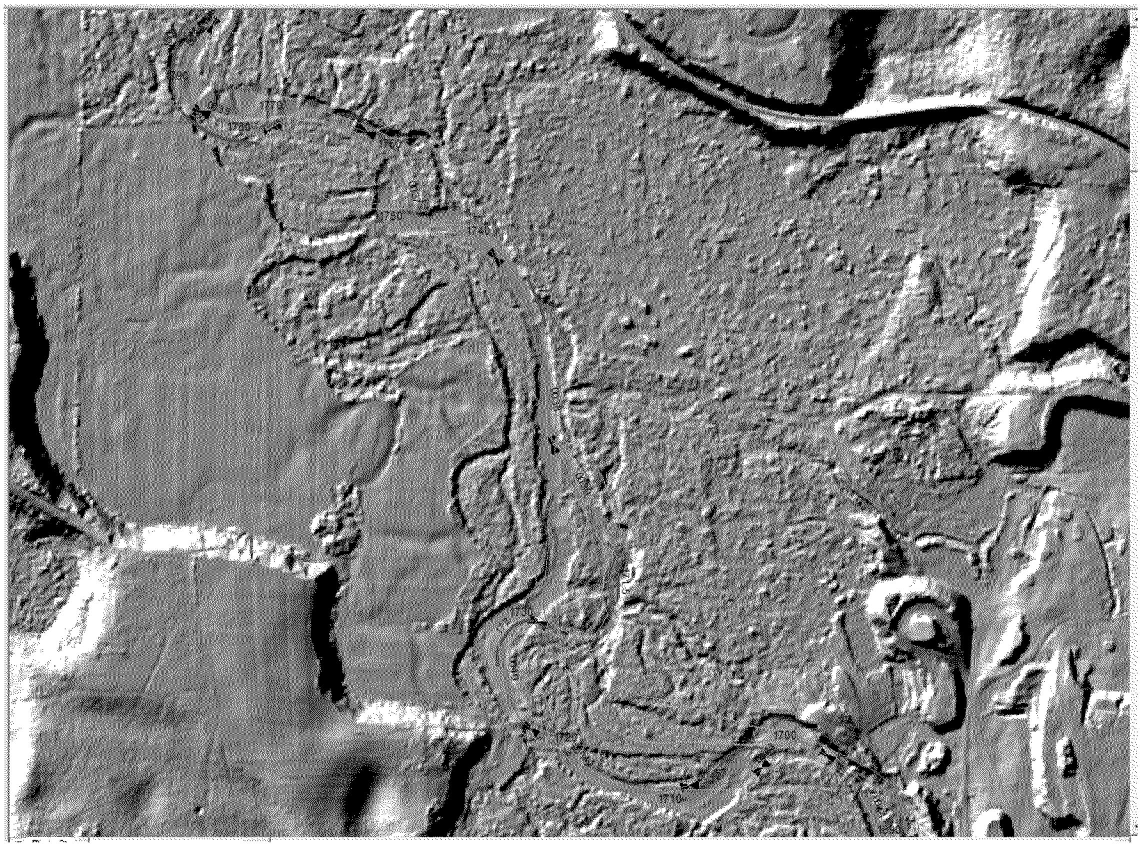

Figure 6. 2003 hillshade LiDAR image of the area shown in Figure 5 with the following superimposed: 1981-1991 bank erosion locations (red lines); 1996 reaches (green line with black arrows); 1991-2003 bank erosion sites (yellow polygons); historic channel locations (light blue lines 1941, dark blue lines 1965, orange lines 1996).

Because erosion of the modern channel and floodplain is a remobilization of sediment already introduced into the river system, sediment from these sources is not considered as a net sediment influx (Reid and Dunne 1996). In order to quantify net influx, all eroded areas were identified as hillslope, glacial terrace, floodplain or low floodplain landforms. Identification of eroded landforms was accomplished by a combination of interpretation from 2003 stereo aerial photographs and LiDAR, Thurston County soil surveys (USDA SCS 1958, Pringle 1990), and field measurements of bank heights from 1993, 1996, and 2005. Landforms assigned as floodplains were also checked against 100-year floodplain mapping by Williams (1976) obtained by projecting water surface elevations of the 100-year flood from stage-discharge relations, instrumented ground elevations, and high-water information from local residents.

The fine sediment fraction (< 2mm) of the net influx was estimated from soil survey sieve data (Pringle 1990) (Table 1). Generally, the lower floodplain surfaces have a larger coarse fraction than higher floodplain soils, which consist primarily of fines. Glacial terraces have a larger coarse fraction except in the Tumwater sand unit of Walsh and others (2003), although most soil test pits capture only the first five feet of any surface.

Table 1. Assignment of coarse and fine fractions of stream-eroded areas based on representative SCS soil survey sieve data (Pringle 1990).

NRCS Soil Unit Number	Average depth of bank erosion (ft)	Soil Depth (in)	Percent > 3 in	Percent <3 in passing 2mm sieve	Assigned Coarse fraction	Assigned Fine fraction
5, 6	14	4-54	15-55	15-40		
		54-60	10-40	20-40	0.775	0.225
7, 8	0.5	0-4	20-40	50-75		
		4-54	15-55	15-40	0.65	0.35
9	6	0-14	0	85-90		
		14-45	0-25	45-85	0.43	0.57
26	6	0-60	0	100	0	1
32, 33, 34	5.5	3-20	5-10	20-50		
		20-60	5-20	15-45	0.7	0.3
41	7.5	0-60	0	100	0	1
46, 48	4.8	60	0	75-100	0.125	0.875
50*	10	22-30	0-10	55-85	0.35	0.65
71	5.2	8-60	0	75-100	0.125	0.875
72	5.8	8-60	0	75-100	0.125	0.875
82	5.5	10-30	15-65	25-60	0.75	0.25
84	5.7	60	0	75-100	0.125	0.875
85 (pits)**	5					
88	6.7	0-60	0	100	0	1
89	5.3	60	0	70-100	0.15	0.85
95	4.4	0-60	0-25	25-50	0.65	0.35
108	17	60	0	85-100	0.075	0.925
110	18	20-60	10-25	20-30	0.8	0.2
115	7.7	0-60	0	100	0	1
126	7	0-60	0	100	0	1

* Soil cemented below 30" with no sieve data
** site 1670 in gravel pit within soil unit 32; assigned soil unit 32 particle distribution but site likely floodplain soils not represented on soil map

4.2 Comparison of Bank Erosion from 1972 to 2003

Bank erosion estimates from 1991 to 2003 are compared with earlier periods in Table 2. As the time periods are not of equal length, annual averages are provided to compare erosion rates between the three periods. Data reported in Collins (1994) was used for bank erosion estimates for the periods of 1972 to 1981 and 1981 to 1991. Collins (1994) quantified bank erosion for two time periods using photogrammetric techniques and field measured bank heights supplemented with data from McNicholas (1984). Collins (1994) also provides the area in bank erosion but not volumes for the periods of 1941 to 1953 (38 acres), 1953 to 1964 (42 acres), and 1964 to1972 (34 acres). No strong correlation is found between eroded area and volume in the three periods from 1972 to 2003, so those results were not extrapolated to the earlier periods.

Table 2. Comparison of bank erosion for the time periods of 1971-1981 and 1981-1991 from Collins (1994, Tables A-3 and A-4 pre-rounded inventory data) and 1991-2003.

	Time Period 1	*Time Period 2*	*Time Period 3*
Measure	**1972–1981**	**1981–1991**	**1991–2003**
Number of erosion sites	94	127	192
Number of glacial terrace erosion sites	24	21	17
Area in bank erosion (acres)	34	56	70
Overall sediment yield (yd^3)	**432,200**	**869,000**	**745,000**
Avg. annual sediment yield (yd^3/yr)	48,000	87,000	62,000
Volume per eroded area (yd^3/ yr/ ac)	1,400	1,550	900
Proportion of total fines (yd^3)	334,100 (77%)	703,000 (81%)	625,400 (84%)
Net sediment influx for period (yd^3)	**108,400**	**332,000**	**101,000**
Avg. annual net sediment influx (yd^3/yr)	12,000	33,000	8,400
Fine sediment portion of net influx (yd^3)	79,600 (73%)	271,000 (82%)	59,000 (58%)
Avg. annual fine sediment net influx (yd^3/yr)	8,800	27,000	4,900
Floodplain erosion (yd^3)	**323,800**	**536,000**	**644,000**
Average annual floodplain erosion (yd^3/yr)	36,000	54,000	54,000

Overall sediment yield from bank erosion measurable from orthophotographs varies between the three periods. Period 1 (1972 to 1981) generated the lowest overall sediment yield of 48,000 yd^3/year and the lowest area in bank erosion of 34 acres. Period 2 (1981 to 1991) included erosion associated with the flood of record in January of 1990 and produced 87,000 yd^3/year, twice as much as the earlier period. Period 3 (1991 to 2003) produced an intermediate amount of bank erosion at 62,000 yd^3/year.

For consistent comparison between the periods, the Collins 1981 to 1991 mapping and data were reviewed to determine landforms of bank erosion sites similar to those used in the 1991 to 2003 erosion sites. Landform associations made for the Collins (1994) work were based on relative height of the eroding bank. Collins assumed six feet as the average height above the channel bed of the contemporary floodplain, and subtracted six feet from all bank heights to calculate the net sediment influx from glacial or relict floodplain surfaces. A number of resources were used to identify landform surfaces, including 1958 and 1990 Thurston County soil survey mapping (USDA SCS 1958, Pringle 1990), LiDAR hillshade or bare-earth images, and floodplain and meander zone mapping in Williams (1976) and Taylor (1999). The erosion site reassignment to landforms consistent with the work made essentially no difference in the distribution of erosion volumes in the original work. Less confidence was placed in identifying the 1972 to 1981 erosion sites, so those data were not re-analyzed and graphed in the same manner for comparison. For the 1972 to 1981 data in Table 2, erosion sites 10 feet or higher were assumed to be of glacial origin.

Sediment from glacial terrace and hillslope sources, or the net sediment influx, during period 2 is three to four times that in periods 1 and 3 and constitutes a larger percentage of the total sediment yield than the other periods (25, 38, and 14 percent) (Table 2, Figures 7 and 8). The greater glacial terrace erosion in period 2 (Figure 8) likely reflects channel behavior during the high magnitude storm of record in January 1990. The larger percentage of floodplain erosion during the 1991 to 2003 period may be more reflective of post-1990 storm sediment redistribution or channel behavior during higher frequency, lower magnitude discharge events. The difference is consistent with a reduction in the number of glacial terrace erosion sites between the later two periods. A greater number of glacial terrace erosion sites in period 1, however, produced less sediment. Erosion from the floodplain, or remobilization of channel stored sediment, during the last two periods is essentially the same at 54,000 yd^3/year (Table 2), and higher than in period 1.

Although more sediment was generated from bank erosion in period 2, period 3 involved a greater number of sites and more area. Measurable bank erosion, or channel shifting, from 1991 to 2003 involved 192 sites and 70 acres compared with 127 sites and 56 acres for period 2 and 94 sites and 34 acres for period 1. Bank erosion rates per area are lowest in period 3, consistent with bank erosion predominantly involving floodplain deposits during this time (Figure 7).

The estimated fine sediment fraction from all bank erosion sources between the three periods was similar at 77, 81, and 84 percent. The difference in the percent of fines from new sources (net sediment influx) between the periods is likely due to more eroding finer-grained glacial terrace sites in periods 1 and 2, and larger erosion volumes in sandy terraces in the lower watershed that have since been stabilized. Differences in the location of erosion sites or the particle size distribution assigned to associated soils may also be factors.

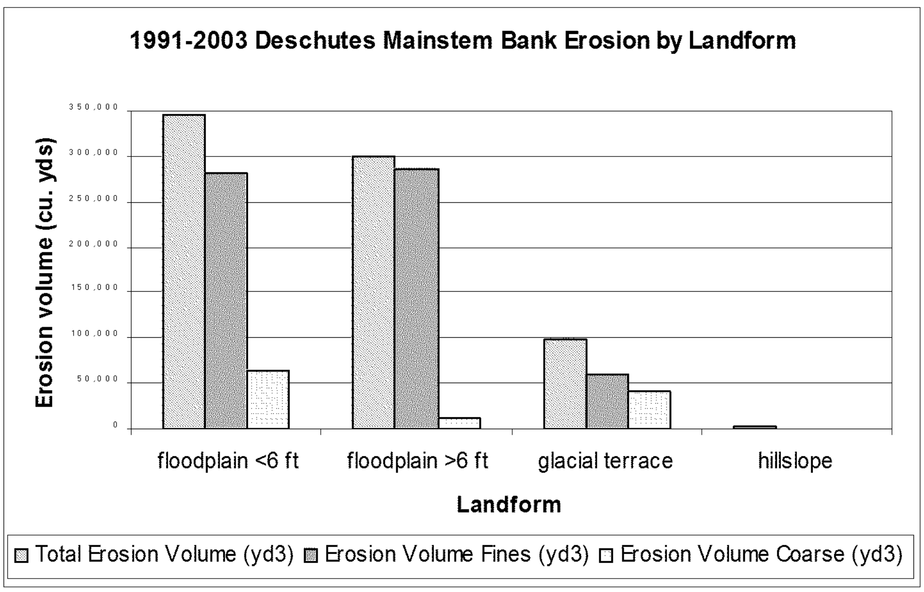

Figure 7. Distribution of Deschutes mainstem bank erosion among landforms for the period of 1991 to 2003.

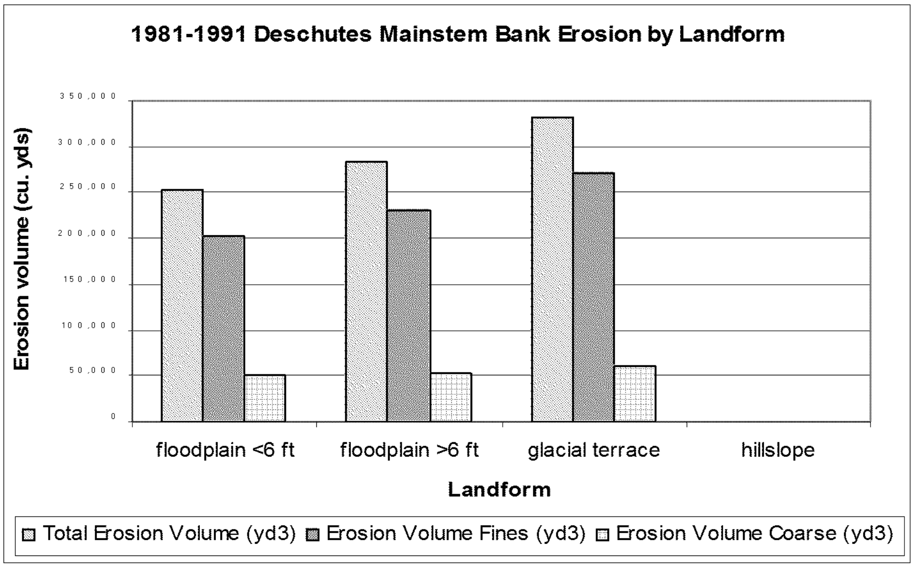

Figure 8. Distribution of Deschutes mainstem bank erosion among landforms for the period of 1981 to 1991.

4.3 Patterns of Bank Erosion

Figures 9 and 10 compare erosion between time periods by reaches defined by McNicholas (1984) and used by Collins (1994) and by geomorphic areas defined in this report. The patterns of erosion are similar between the time periods (Figure 9); however, erosion in 1972 to 1981 increases downstream at a lower rate. Few reaches have no bank erosion (Figure 10). Several locations show a downstream shift in erosion location between 1981 to 1991 and 1991 to 2003. The number of 2003 sites corresponding to those reported in the 1991 photos and 1993 field work is 89, or 44 percent. Within the recessional sand and kettle area, erosion is concentrated between reaches 1 and 7, where the valley is bounded almost entirely by terraces in the Tumwater sand unit. Also evident is a significant difference in bank erosion in segment 2 between 1991 and 2003, attributable to stabilization of a high sandy glacial terrace at site 1860 in the latter period.

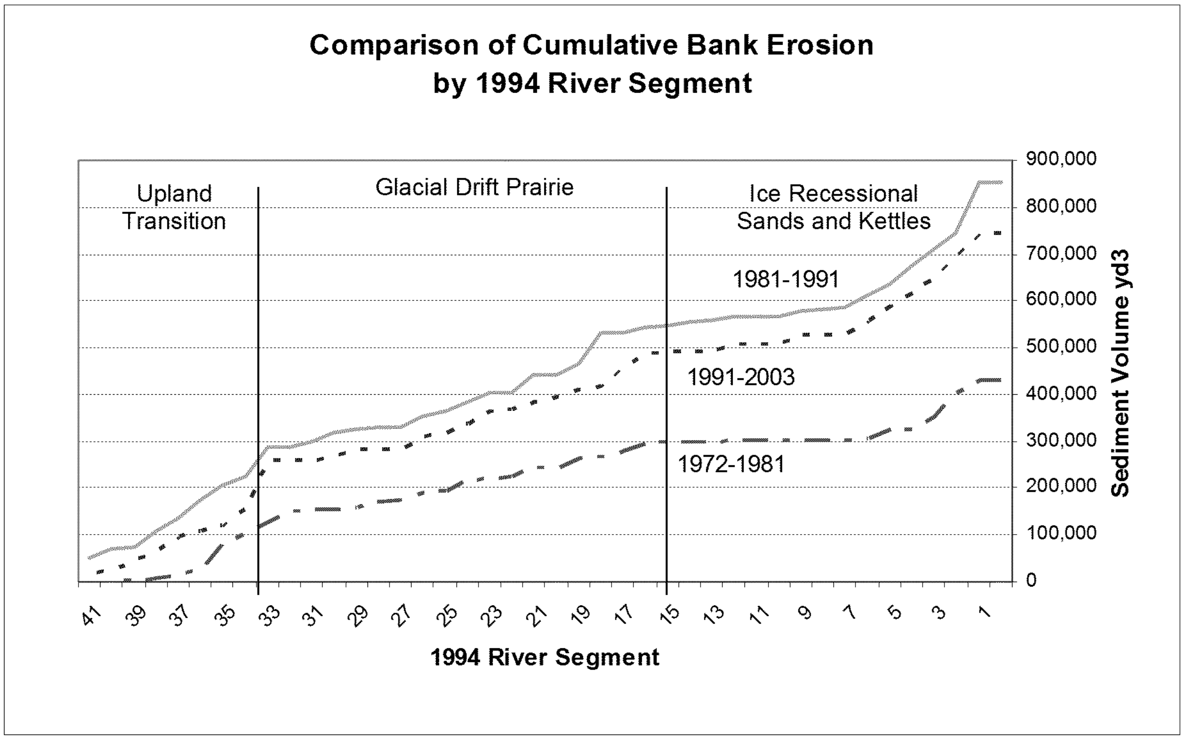

Figure 9. Graph of cumulative bank erosion by river segments for the time periods of 1972-1981 and 1981-1991 (Collins 1994) and 1991 to 2003. Upstream to downstream is from left to right.

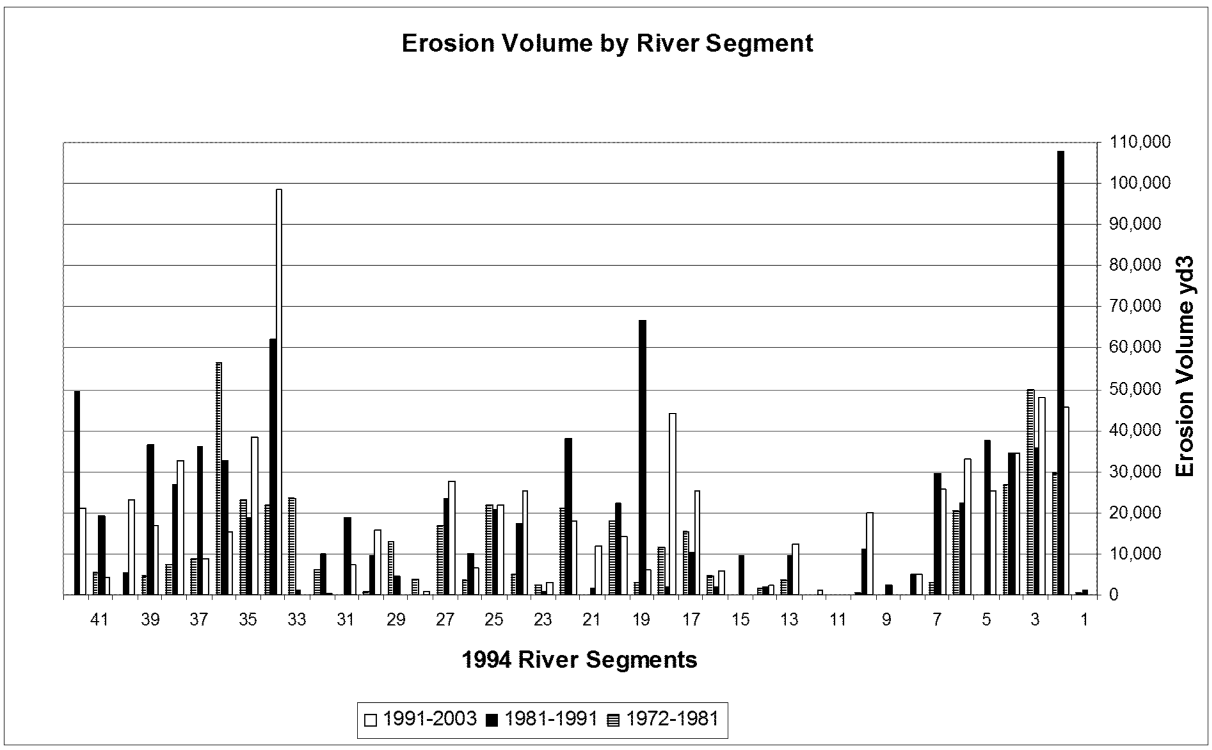

Figure 10. Graph of erosion volume by 1993 river segments for the time periods of 1972-1981 and 1981-1991 (Collins 1994) and 1991 to 2003. Upstream to downstream is from left to right.

To compare erosion locations and volumes in equal units between time periods, bank erosion rates were calculated by river valley length in each geomorphic area (Figure 11). River segments as originally defined by McNicholas (1984) are of unequal length, and river miles defined in Williams et al. (1975) and Williams (1976) are not consistent. The length of river is subject to change over time in some reaches, while valley length stays constant. The ratio of channel length to valley length also provides a measure of channel sinuosity useful for predicting local channel migration and erosion potential, although river valley miles are not provided in this report.

Bank erosion rates calculated by valley length measured down the center of the Deschutes River floodplain as defined by Williams (1976) produced a pattern of erosion consistent between the three geomorphic areas and time intervals (Figure 11). Although results vary by time period, bank erosion per unit valley length is essentially equal in the upstream and downstream areas and three to four times greater than in the prairie area.

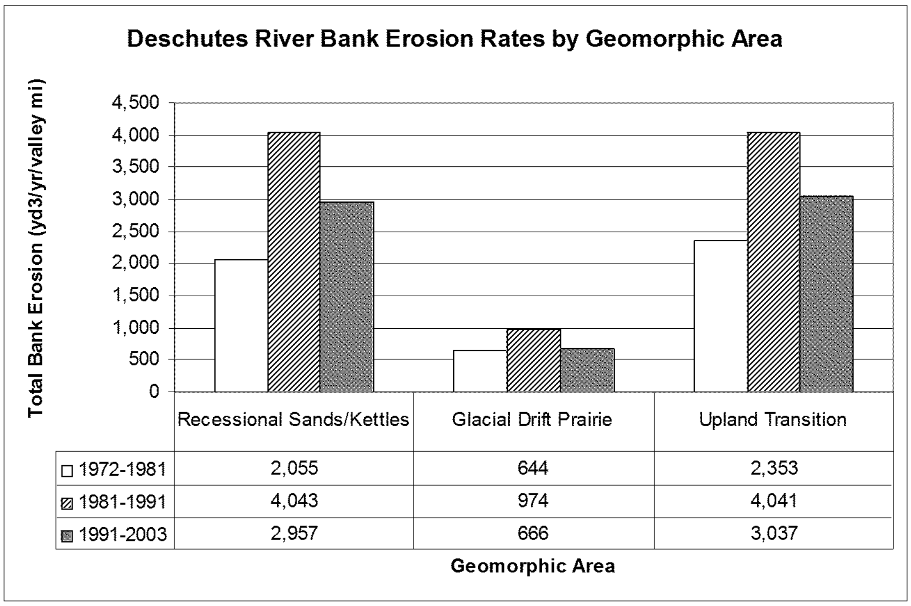

Figure 11. Comparison of Deschutes River mainstem bank erosion rates by valley mile for three geomorphic areas and three analysis periods.

Collins (1994) found higher rates and volumes of bank erosion where the river flows through a narrow valley between glacial terraces and reaches of declining channel gradient. Reaches of declining gradient are also associated with sediment deposition that occurs upstream of channel constrictions. As an example, Williams (1976) notes falls of 1.1 and 1.4 feet in the 1974 peak flow water surface profiles through constrictions at two bridges on the mainstem Deschutes River.

Channel constriction features associated with erosion sites are listed in Table 3 and are located on the figures in Appendix E. Excluded from the list are lower reaches 1 through 15, as interpreting the link between channel constrictions and the high incidence of bank erosion is complicated by the high natural sinuosity of the channel and incomplete information on bank armoring locations in the increasingly urbanized landscape downstream. Erosion associated with both natural and anthropogenic channel constrictions within reaches 16 to 42 accounts for 70 percent of the 1991 to 2003 bank erosion volume in those reaches. Natural constrictions account for approximately 40 percent and anthropogenic constrictions approximately 30 percent of the total. This is not to say that erosion would not have occurred in the absence of the anthropogenic constrictions, but that the locations and extent of erosion is directly linked to them.

Table 3. Areas of concentrated 1991-2003 bank erosion associated with channel constrictions in segments 16 to 42 of the mainstem Deschutes River.

2003 Erosion Sites	Affected Segments[2]	Associated Features and Location
150-131	39	Slight narrowing of valley at erosion site 131 and streamside rural housing area with some bank protection immediately downstream may contribute to erosion in lowest portion of natural sediment deposition area below Deschutes Falls.
170-160	38	Natural valley constriction just downstream of erosion site 170
180-220	37	Valley fill and bank protection approximately 1000 ft above and below Weyerhaeuser 1000 road bridge likely forcing tight meanders and some of the floodplain and terrace erosion upstream between bridge and the valley constriction below erosion site 170.
230-260	36	Natural valley constriction immediately downstream of erosion site 260
280 - 360	34.5-35	Natural valley constriction at erosion site 370 located at the lower end of the upland transition area; this eroding area is most downstream large sediment sink.
370-400	34.0-34.5	Bank protection along most of reach 33 likely forcing smaller scale erosion upstream of the section line boundary beginning at erosion site 400
540-580	30	Smaller scale erosion immediately upstream of Vail Loop Road crossing at RM 29.4; likely some bank protection in place locally
650-720	Lower end of 27	Natural valley constriction immediately downstream of erosion site 720
810-850	25	Valley constriction by highway 507 and BN railroad crossings
860-910	24	Suspected armoring of banks in the vicinity of right bank erosion site 900 just downstream of Highway 507 crossing; bioengineering parcel on right bank throughout eroding reach.
1010-1030	22	Valley constriction associated with the Waldrick Road crossing; bank protection likely limiting the extent of erosion.
1040-1090	20-21	Natural valley constriction and meander cut-off by railroad grade downstream and adjacent to erosion site 1090
1130	18	Right bank armoring immediately downstream of erosion site 1130 likely forced erosion of 1.5 ac
1190-1240	17	Bank erosion immediately upstream of bioengineering parcel; channel spanning debris jam also in middle of eroding sites
1260-1280	16	Valley constriction and armoring at Rich Road and pipeline crossings immediately downstream of erosion site 1280

[2] McNicholas (1984) and Collins (1994) segment numbering.

The locations and extent of bank armoring, particularly in the floodplain, also influence the locations and extent of bank erosion. No inventory of bank armoring sites was conducted for this study; however, Collins (1994) measured bank protection locations along the 60 percent of the mainstem reaches field surveyed, which excluded reaches 23 through 31 in the glacial drift prairie. Bank armoring in the surveyed reaches averaged 10.4 percent of all banks; 11.9 percent of left bank and 8.8 percent of the right bank. Bank armoring is concentrated in reaches 7 through 21 with 12.5 percent of all banks armored, which would explain the low bank erosion volumes in this area (Figure 9). A number of bank stabilization projects using bioengineering techniques are located in reaches 2, 3, 12, 13, 14, 17, 18, and 24 (Figure 12). Locations where bank armoring is likely include banks adjacent to bridges and reaches with adequate floodplains that are low or lacking in inventoried bank erosion sites.

Cramer (1997) estimated percent bank armoring by reach for the mainstem between the falls. A tally of percent armoring of reach length from the Cramer data suggests that 45 to 50 percent of banks along the entire Deschutes mainstem are armored, which is high compared with the Collins data. It's not clear from the data collection instructions, but these are likely estimates and not measurements. Reliability of some of these data may be questionable (email communication, D. Cramer July 6, 2005).

Figure 12. Locations of bioengineering bank stabilization parcels.

5.0 SEDIMENT ESTIMATES FROM OTHER SOURCES

Sediment estimates from other sources evaluated here are limited to landslides and surface erosion from unpaved roads. After mainstem bank erosion, landslides and roads are the likely major sediment sources in the watershed, and methods exist to roughly estimate those sediment inputs. A comparison of sediment from estimated sources found in Section 6 indicates that mainstem bank erosion, headwater landslides, and surface erosion of unpaved roads account for the majority of sediment exiting the system on an averaged annual basis.

We did not consider sediment estimates from stream bank erosion in the tributaries or from agricultural, urban run-off, or other land use sources. Sediment delivery to the mainstem from bank erosion in the few tributaries downstream of Fall Creek is considered nominal due to low gradients, small drainage areas, or sediment-trapping wetlands in the lower reaches (Collins 1994). Evaluating water quality data in the lower watershed tributaries to quantify sediment input from other land use sources is possible but was out of scope to this project. Erosion in the high gradient headwater tributaries is dominated by mass wasting and debris flow processes, consequently bank erosion in upper watershed tributaries is at least partially quantified in the landslide inventory.

5.1 Sediment from Landslides

The Weyerhaeuser Company provided an updated landslide inventory for their ownership in the upper watershed (Appendix C) for use in this report. This area includes most of the landslide sources in the watershed not already identified as stream bank erosion sources in Section 4 above. Both Collins (1994) and this work rely on landslide mapping provided by Weyerhaeuser. The landslide inventory used here differs from Collins (1994) in that sediment volumes delivering to streams from all landslides have been estimated. Collins (1994) quantified landslide volumes originating from locations capable of directly routing coarse sediment to the mainstem (38 percent of landslides) and extrapolated those results to landslides and debris flows in tributaries where coarse sediment could be deposited in the lower reaches.

5.1.1 Methods

The landslide inventory covers the period from 1966 to 2001 and includes all landslides visible on aerial photographs along with an estimate of the volume of sediment delivered to streams during the inventory period (Ted Turner, Weyerhaeuser Company geologist, personal communication 2005). The updated landslide inventory is considered provisional by the Weyerhaeuser Company, as not all photograph-identified features and landslide volume estimates have been field verified or reconciled with earlier inventories. Slightly different aerial photograph series from the earlier inventory were used in the updated inventory, and some years were missing photographs.

Appendix C contains the provisional landslide map as provided by the Weyerhaeuser Company and landslide inventory data reconciled with the map. Landslide features identified from aerial photographs as "questionable" were not included in the volume estimates of sediment delivering to streams. Two landslides duplicated in our bank erosion inventory below Deschutes Falls were also removed from the sediment estimates (numbers 100 and 531). Most if not all of the large deep-seated failures identified were not assigned any estimated rate of measurable erosion to the stream system during the inventory period.

5.1.2 Landslide Sediment Estimates

A total of 110 landslides with sediment delivery to streams were inventoried between 1966 and 2001 (Appendix C). Landslides inventoried in 1966 aerial photographs were not included in the summary as those features occurred prior to 1966 and are not time constrained. The 1987 to 1990 time period produced the largest rate of landslide sediment volume (Table 4), during which time the peak discharge on record of 9,600 cfs occurred in January of 1990. The second highest peak flow of 7,850 cfs in February of 1996 produced a slightly lower average of landslide volume likely attributable to improvements in forest practices. The third and fourth highest peak flows of 7,780 cfs in January of 1974 and 7,420 cfs in January of 1972 correlate well with the rate of landslide sediment produced in the 1970 to 1978 time period. The remaining time periods show no strong relationship to peak flows (Figure 13).

Table 4. Summary of landslide sediment delivered to streams in the upper Deschutes River basin from 1966 to 1970.

Land Use Association	Sum of Delivered Sediment (yd^3)								
	1966-1970	1978	1983	1987	1990	1993	1999	2001	Grand Total
Non-road	2,292	10,227	2,150	3,770	21,903	1,570	10,230	1,819	53,962
Road	1,852	50,677	22,175	7,037	39,085		27,613		148,440
Blank	1,633								1,633
Total	**5,778**	**60,904**	**24,326**	**10,807**	**60,989**	**1,570**	**37,843**	**1,819**	**204,035**
Annual avg. (yd^3/yr)	*1,445*	*7,610*	*4,865*	*2,700*	*20,330*	*520*	*6,300*	*910*	*5,830*

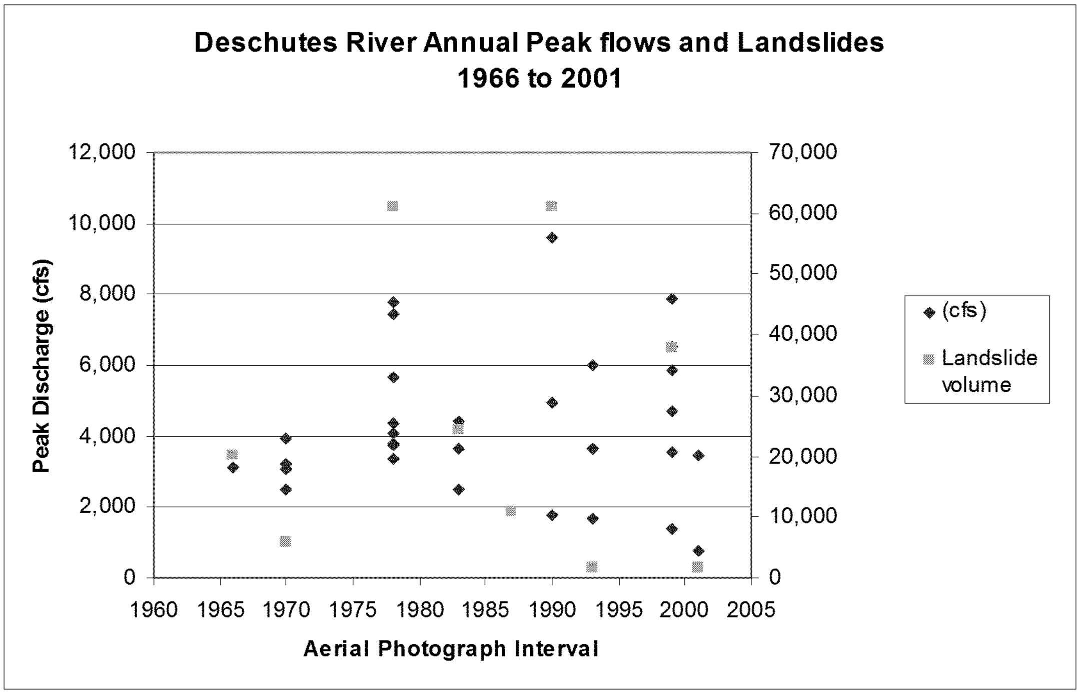

Figure 13. Graph of stream delivered landslide volumes and annual peak flows occurring within each time period of the landslide inventory.

Landslides associated with roads account for 73 percent of the sediment estimate from 1966 to 2001. Landslide features were inventoried as either associated with roads or not. The majority of non-road associated features can be assumed to be directly or indirectly associated with harvest as most of the area had been harvested during the inventory period and the terrain appears to have a naturally low potential for shallow landsliding (Thorsen and Othberg 1978).

Landslides are concentrated in the Mitchell, Lincoln and Lewis Creek drainages located within the east-west belt of weathered bedrock terrain in the upper watershed (Section 2.2; Appendix C). Based on terrain mapping by Thorsen and Othberg (1978), 79 percent of the 110 landslides delivering sediment to streams occurred in weathered bedrock terrain. Much of this terrain has deep, fine-textured soils and deeply weathered bedrock containing a high proportion of silt and clay (Thorsen and Othberg 1978, Pringle 1990). Of the remaining landslides, 14 percent occurred in glacial deposits in the lower watershed and seven percent occurred in unweathered bedrock terrain in the upper headwaters.

The primary soils mapped within the weathered bedrock terrain are the Baumgard-Wilkeson and Pheeney-Mal associations (Pringle 1990). Soil survey sieve data for these soils (Table 5) indicates a greater proportion of soil particles passing a 2mm sieve. Based on these data, the percent of fines from the majority of landslide sediment as introduced to stream channels is conservatively assumed to be 60 percent. Using particle attrition assumptions from Collins (1994) of a 20 to 30 percent reduction of bedload material to suspended sediment during river transport of between 5 and 10 miles, fine sediment from landslide sources upon arrival to the mainstem study reach is estimated at 70 percent of the total, or 142,800 yd^3 (4,100 yd^3/yr). This is likely an underestimate due to the weak nature of the bedrock in the main source areas.

Table 5. Assignment of coarse and fine fractions of landslide sediment in weathered bedrock terrain based on representative SCS soil survey sieve data (Pringle 1990).

NRCS Soil Unit Number	Soil Map Unit Name	Soil Depth (in.)	Percent > 3 in.	Percent <3 in. passing 2mm sieve	Averaged Coarse fraction for soil profile	Averaged Fine fraction for soil profile
10	Baumgard	0-14	0	85-90	0.43	0.57
		14-45	0-25	45-85		
124	Wilkeson	0-11	0-5	85-100	0.26	0.74
		11-47	0-5	60-90		
		47-60	0-5	55-80		
80	Pheeney	0-10	0	55-75	0.62	0.38
		10-30	15-65	25-60		
61	Mal	0-7	0	100	0	1.00
		7-60	0	100		

The updated landslide inventory produced sediment estimates over two times those reported in Collins (1994). A comparison of those results is in Table 6. Based on Collins (1994) estimate of landslide sediment that would persist as coarse sediment to the study area, he estimates between 54,000 – 67,000 yd^3 of fine sediment were transported to the mainstem during the period of 1966 to 1990 (2,250 to 2,800 yd^3/yr). Collins (1994) estimated tributary or upland suspended sediment yield from all sources at about 8,700 yd^3/yr based on data in Sullivan et al. (1987) and Moore and Anderson 1979). Fines from both the revised landslide inventory and estimates of road surface erosion in the following section total 6,900 yd3/yr, indicating that roads and landslides may account for much of the measured suspended sediment in the upper watershed.

Table 6. Comparison of estimated sediment from landslides from Collins (1994) and 2001.

	1966-1990 Landslide sediment[1]	1966-1990 Landslide sediment estimate to mainstem [1]	1966-1990 revised landslides	1990-2001 landslides
Bedload yd^3	49,000	11,000 – 24,000	48,800	12,000
Fines yd^3	49,000	54,000 – 67,000	114,000	29,000
Total yd^3	98,000	78,000	162,800	41,000
yd^3/yr	4,100	3,250	6,800	3,750

[1] From Collins (1994); number includes estimates from landslides delivered directly to the Deschutes River less tributary-stored landslide deposits

Based on the available information and a sediment budget approach, all sediment introduced to streams from hillslopes by landslides represents a net sediment influx to the Deschutes River basin channels. Subsequent routing and channel-stored residence times are not well constrained. However, as 79 percent of landslides originate in the weathered and fractured bedrock and the Sullivan et al. (1987) data suggest that landslide channel-stored sediment in the headwaters routes relatively quickly, we assume that all of the landslide-derived sediment has routed to the mainstem study reach within the period of interest. In addition, a comparison of several landslides found in Sullivan et al. (1987), Collins (1994), and the updated Weyerhaeuser map (Appendix C) show the volumes associated with same landslides in the new inventory to be one half or less than the earlier estimates, suggesting a potential for underestimated landslide volumes in the provisional data.

5.2 Sediment Estimates from Unpaved Roads

Surface erosion from forest roads in the Pacific Northwest is well-documented to produce fine-grained sediment (generally 2 mm or less) easily transported to streams via ditch-lines and drainage points during most rainfall events (Gucinski et al. 2001). Since approximately 60 percent of all roads in the Deschutes River basin are unpaved, surface erosion from unpaved forest, county and private roads was roughly estimated using a road sediment model to determine if collectively they are a potentially significant source of fine sediment compared with bank erosion sources.

5.2.1 Road Sediment Estimate Methods

The Washington Road Surface Erosion Model, or WARSEM (Dubé et al. 2004), was used to estimate surface erosion from unpaved roads. WARSEM is a recent revision of an empirical road surface erosion model found in the Washington Forest Practices Board Standard Methodology for Conducting Watershed Analysis (1997) http://www.dnr.wa.gov/forestpractices/adaptivemanagement/warsem. The model was built in part from data from the Deschutes River watershed (Sullivan and Duncan 1980, Bilby et al. 1989) and is appropriate for use there. WARSEM was developed as a standardized Access© database application, and calculates an average annual sediment yield to streams based on road attributes entered into the program. The amount and detail of input to run the model is flexible depending on the application and the amount of information available on the roads. The screening Level 1 application of the model was used for this analysis, which allows user input of some road attributes appropriate to the level of data derived from GIS and aerial photograph analyses. Appendix C contains a summary of methods and a discussion of model input data and assumptions.

5.2.2 Summary Results of Road Sediment Modeling

The available road data show 1,033 total miles of road within the Deschutes basin, and 611 miles were identified as unpaved roads (Figure 14). Using the road connectivity assumptions in Appendix D, 192 miles or 31% of the length of all unpaved roads are directly connected to streams and an additional 96 miles or 16% fall within 200 feet of a stream. Comparing these numbers with published data shows this is a reasonable and perhaps underestimated assumption. Sullivan et al. (1987) reported 33% direct entry of roads in a 1979 survey of the Deschutes River watershed. Bilby et al. (1989) found that 34% of road structures discharged directly to streams, while La Marche and Lettenmaier (2001) found that 45% and 57% of culverts in Hard and Ware Creeks in the upper Deschutes River were connected to streams by either direct entry at stream crossings or by gullying of the slope below relief culverts.

Figure 14. Deschutes River basin with Roads by type.

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Data generated by GIS to input into the model included length of road connected to streams in two connectivity classes, two road classes that reflect traffic levels, and three geologic erosion factors (Appendix D). Two runs of the model were made by varying road surface conditions to help bracket potential erosion estimates (Table 7). As the difference between the two surfacing categories is a factor of two in the model, the second run is essentially double the first. To allow comparison with bank erosion estimates, modeled road sediment in tons was converted to volume in cubic yards using an estimated bulk density of 1.5 Mg/m^3 (1.26 $tons/yd^3$), an approximate value for soil (Washington Forest Practices Board 1997).

Table 7. Summary of road modeling results as average annual sediment yield in yd^3.

Road Class	Length (miles)	Geologic Erosion Factor	Connectivity	Road Sediment Gravel surfacing (yd^3/yr)	Road Sediment Gravel w/ruts (yd^3/yr)
Main haul road	9.1	low	direct to stream	221	442
Main haul road	2.3	moderate	direct to stream	110	220
Main haul road	4.0	low	partial w/in 200’	10	19
Main haul road	1.2	moderate	partial w/in 200’	6	12
Other unpaved roads	159.9	low	direct to stream	1,074	2,149
Other unpaved roads	10.7	moderate	direct to stream	144	288
Other unpaved roads	9.9	high	direct to stream	333	665
Other unpaved roads	76.9	low	partial w/in 200’	52	103
Other unpaved roads	5.6	moderate	partial w/in 200’	7	15
Other unpaved roads	8.6	high	partial w/in 200’	29	58
Totals	288			1,986	3,971

Sullivan et al. (1987) estimated average sediment contributions from road construction and traffic use on Weyerhaeuser forest roads in the Deschutes basin. They estimated road construction at the then current rate of 10 km/yr to produce 650 tonnes (716 tons) of sediment annually based on increased sediment yields measured in two small tributaries underlain primarily by unweathered rock in the headwaters. Road construction from 1975 to 1978 peaked at 27 km/yr with estimated annual sediment contributions as much as 1,900 tonnes (2,090 tons). Sediment from log truck use of 511 km (317 miles) of road in 1980 was estimated based on experimental results of Reid and Dunne (1984) using a 1979 inventory of road length and surface with direct entry culverts, turbidity grab samples in the tributaries, and estimated traffic use rates as a function of harvest. They estimated the amount of sediment from roads during a normal rainfall year at 250 to 500 tonnes (275 to 551 tons) per year. Together, construction and use of roads was estimated to deliver 900 to 1,150 tonnes (992 to 1,268 tons) annually, or 9.5–11 tons per mile per year from the 33% of the roads with direct delivery. This compares to model estimates in this report of 12–25 tons per mile per year for the 192 miles of direct delivering roads with no new road construction assumed.

5.2.3 Road Sediment Discussion

Modeled fine sediment from unpaved roads is between 40 and 80% of the average annual net fine sediment influx from bank erosion for the 1991 to 2003 period. Modeling results suggest that fine sediment contributions from roads may be a more significant portion of total sediment influx during periods of lower glacial bank erosion contributions. In addition, the timing and duration of fine sediment transport differs between road and bank erosion sources. Road sediment would be mobilized to streams during many or most precipitation events and be more detectible in tributary streams, while sediment input from measurable bank erosion is episodic and related to high flows and bed-mobilizing events in the mainstem.

A recent analysis of 30 years of water quality data compiled by Weyerhaeuser in the upper Deschutes River shows a decreasing trend in turbidity since about the mid-1990s while other hydrologic parameters show no trend (Reiter et al. 2005). One explanation made for the decrease in turbidity is a major road renovation effort, suggesting that the influence of forest roads on turbidity is detectible, although interpretation of turbidity trends were made difficult due to simultaneous events of harvest reduction, and therefore decreased truck traffic, and the elimination of broadcast burning.

The results of this exercise suggest that a more detailed assessment of the fine sediment contribution from roads is warranted for better estimating road sediment and targeting sources for fine sediment reduction. The simplifying assumptions used in this application of the road erosion model contribute to both over and under estimating results. For example, traffic on spur roads is likely over estimated, and only sediment from the road running surface and ditch was modeled as no data were available on height, length, and cover condition of the cutslope portion of the road prism. Published data (Bilby et al. 1989, Bowling and Lettenmaier 1997) also suggest that road connectivity to streams may be greater than the assumptions used in the modeling exercise for pre-forest road renovation conditions. Road sediment can be better estimated by using road segment-specific data in the model and/or SEDMODL2 www.ncasi.org/forestry/research/watershed.stm, a GIS-run version of the model that uses topographic DEMs to approximate road sediment delivery to streams. Modeling pre and post-road renovation conditions may also correlate well with trends in the Weyerhaeuser turbidity data.

6.0 COMPARISON OF SEDIMENT SOURCE ESTIMATES

A rough sediment budget for the Deschutes River (Table 8) was constructed for three time periods, from 1972 to 2003, based on available information and data provided in this report (Sections 4 and 5). Sources of data in Table 8 are footnoted below. Sediment from floodplain bank erosion is not included as a sediment source but is considered in a discussion below on floodplain sediment storage and transfer. Sediment accumulation at the mouth of the river (sediment output) is estimated from bathymetry and dredging in Capitol Lake as summarized from previous work in George et al. (2006), who also calculated a similar estimate of 33,000 yd^3/yr (25,200 m^3/yr) by applying a 1974 rating curve to the river hydrograph. Because sediment output has been estimated, the change in channel-stored sediment is derived by subtracting sediment output from the input sources, and the sediment budget equation becomes:

$$Input - Output = \Delta Storage$$

To facilitate comparison of these results with previously issued reports, sediment volumes are reported in units of cubic yards or a rate of cubic yards per year. Because the bank erosion, landslide, and sediment accumulation analysis periods are not the same, only the annual averages were used to calculate the net change in channel sediment storage for the individual time periods. Since not all sediment sources are accounted for, only generalizations and reasoned hypotheses can be concluded from this exercise.

Weyerhaeuser results (Sullivan et al. 1987) are used to estimate road sediment contributions in the earlier analysis periods for the sediment comparison as the estimates are derived from local data and they are assumed to represent the majority of unpaved roads in the watershed at that time. The average of the two road sediment model runs in this report was used for the 1991 to 2003 analysis period. The difference in road sediment rates and totals between the periods is a function of both the manner in which road sediment rates were calculated (Section 5) and the difference in the miles of unpaved roads. The Sullivan et al. (1987) estimates apply to the 317 miles of existing road on Weyerhaeuser ownership in 1980, and this report modeled road sediment from 611 miles of unpaved roads throughout the basin as of 2005.

An average change in storage (net loss) of -7,000 to -12,000 yd^3/yr of sediment is estimated for the 31-year period (Table 8). It appears that net sediment excess in the 1981-1991 period was exported in the following period when sediment influx fell. The negative numbers likely represent unquantified sediment sources mentioned in the introduction to Section 5.0 and errors in sediment estimates. Gravel scalping or mining (sediment export) noted by Collins (1994) would also contribute to a net reduction in sediment discharge, although this was not investigated.

Since some sediment sources are unaccounted for and there are potentially large estimate errors, we cannot assume the system is degrading based on the negative change in storage totals. There is also little or weak evidence of aggradation. Collins (1994) could find no pattern of net channel widening over time in measurements of channel width from aerial photographs in areas of bank erosion from 1941 to 1991. Nelson (1974) also notes that stream channels appear fairly stable. Nelson (1974) found that more suspended sediment is transported past the Olympia sampling site during years of high streamflow while more sediment is transported past the mid-river Rainier site during years of medium and low streamflow. He assumed that much of the sediment passing the upper site was deposited temporarily in the reach between the two sampling sites and later transported by lesser streamflows. The low percent of bedload to suspended sediment discharge in the river (Nelson 1974) may explain the moderate channel response to increased sediment influx. Annual sediment discharge values based on sediment accumulation in Capitol Lake vary by 26,000 yd^3 (20,000 m^3) (George et al. 2006), and part if not all of the channel storage deficit could be accounted for in the range of reported annual sediment volumes.

Table 8. Sediment budget summary for the Deschutes River by volume and approximate time period.

	Sediment (yd^3)				
SEDIMENT SOURCES					**Total (yrs)**
High bank erosion		**1972-1981[3]**	**1981-1991[4]**	**1991-2003[5]**	**1972-2003 (31)**
Fines		79,600	271,000	59,000	409,600
Coarse		28,800	61,000	42,000	131,800
Total		108,400	332,000	101,000	541,400
Annual Average yd^3/yr		*12,000*	*33,000*	*8,400*	*17,500*
Landslides[6]	**1966-1970**	**1970-1978**	**1978-1990**	**1990-2001**	**1970-2001 (31)**
Fines	4,060	42,600	67,300	28,800	138,700
Coarse	1,740	18,300	28,800	12,400	59,500
Total	5,800	60,900	96,100	41,200	198,000
Annual Average yd^3/yr	*1,450*	*7,600*	*8,000*	*3,750*	*6,400*
Unpaved roads		**1972-1981[7]**	**1981-1991[8]**	**1991-2003[9]**	**1972-2003 (31)**
Fines		11,400	9,000	36,000	56,400
Annual Average yd^3/yr		1,270	*900*	*3,000*	*1,800*
Other sources		?	?	?	?
TOTAL FINES		133,600	347,300	123,800	604,700
TOTAL COARSE		47,100	89,800	54,400	191,300
TOTAL		180,700	437,100	178,200	796,000
***Annual Average** yd^3/yr [10]*		*20,900*	*42,000*	*15,200*	*25,700*
SEDIMENT OUTPUT	**1952-1974**	**1974-1983**	**1983-1990**	**1990-1998**	**1972-2003 (31)**
Annual Average yd^3/yr	*30,000*	*55,000*	*35,000*	*29,000*	*33,000-38,000[11]*
sediment accumulation					
at Capitol Lake					
MAXIMUM[12] NET CHANGE IN STORAGE					
(Input – Output = ΔStorage) yd^3/yr		-34,000	+7,000	-14,000	-7,000 to -12,000

[3] Collins (1994) from Table A-4 pre-rounded inventory data
[4] Collins (1994) from Table A-3 pre-rounded inventory data
[5] This report
[6] This report; landslide data from 1966-1970 not included in total; annual average used in sediment source annual average as analysis periods are not the same or of the same length
[7] Sullivan et al. (1987); used 1900 tonnes/yr estimate for peak road construction years 1975-1978 & 1.5 bulk density
[8] Sullivan et al. (1987); current (1987) annual estimate extrapolated to 10 yr period of 1981-1991
[9] This report; average of annual range extrapolated to 12 yr period of 1991-2003 bank erosion analysis
[10] Annual average for each source used in total sediment source average for each analysis period as not all are the same; totals and averages for 31 year total use both totals and average totals
[11] George et al. (2006); low estimate from 25,200 m^3 rating curve estimate; high estimate from averaging sediment accumulation data: 1952-1974 rate used for 1972-1974 and 1990-1998 rate used for 1998-2003
[12] Since not all sediment sources have been quantified, net change in channel stored sediment is a maximum estimate.

To aid interpretation of the sediment budget exercise as it applies to TMDL development, Table 9 summarizes sediment influx from those anthropogenic sources estimated in this report. As landslides were inventoried as either road-related or not, the lower range of sediment volume for landslides reflects the assumption that only road-related landslides are related to forest management. The higher number assumes that all non-road associated features are directly or indirectly associated with harvest, as most of the area had been harvested during the inventory period and the terrain appears to have a naturally low potential for shallow landsliding (Thorsen and Othberg 1978). All sediment from unpaved roads is assumed anthropogenic in nature.

In the context of the entire watershed area, anthropogenic sources range between 16 and 44 percent or an approximate average of 28 percent of the total. As the quantified anthropogenic sediment sources are located in the upper watershed area[13], Table 9 also includes a comparison of sediment source totals in just the Upland Transition Zone. Over the analysis period, anthropogenic sources constitute approximately 50 percent of the total sediment input in that area. The estimate varies between the three time periods from 30 to 80 percent, depending on the extent of glacial terrace erosion during any period and assumptions on land use associated with landslides. Fines comprise 78 percent of the total from anthropogenic sources and 26 to 32 percent of fines from all sources.

[13] All sediment estimated from unpaved roads is included in the Upland Transition Zone estimate as the portion downstream of this area was not analyzed for the purpose of this comparison. However, the proportion of road sediment outside of the Upland Transition Zone is likely small due to the fewer lengths of road and lower drainage density and stream crossings.

Table 9. Estimate of the proportion of sediment introduced to the Deschutes River from quantified anthropogenic sources from the approximate bank erosion analysis period of 1972 to 2003.

	Sediment (yd^3)				
SEDIMENT SOURCES				**Total**	**Percent of Total**
Landslides[14]	**1970-1978**	**1978-1990**	**1990-2001**	**1970-2001**	
Fines	35,500-42,600	47,800-67,300	19,300-28,800	102,600-138,700	74 - 100
Coarse	15,200-18,300	20,500-28,800	8,300-12,400	44,000-59,500	74 - 100
Total	50,700-60,900	68,300-96,100	27,600-41,200	146,600-198,000	74 - 100
Annual Average yd^3/yr	*6,300-7,600*	*5,700-8,000*	*2,500-3,750*	*4,700-6,400*	
Unpaved roads	**1972-1981**[15]	**1981-1991**[16]	**1991-2003**[17]	**1972-2003**	
Fines	11,400	9,000	36,000	56,400	100
Annual Average yd^3/yr	*1,270*	*900*	*3,000*	*1,800*	
Other anthropogenic sources	?	?	?	?	?
TOTAL FINES	46,900-54,000	56,800-76,300	55,300-64,800	159,000-195,100	81 - 100
TOTAL COARSE	15,200-18,300	20,500-28,800	8,300-12,400	44,000-59,500	74 - 100
TOTAL	62,100-72,300	77,300-105,100	63,600-77,200	203,000-254,600	80 - 100
Annual Average of Anthropogenic Sources	**7,600-8,900**	**6,600-8,900**	**5,500-6,750**	**6,500-8,200**	
Annual Average of all Sources in Upland Transition Zone	17,160	20,260	8,360	14,900	
Percent Anthropogenic Sediment Sources in Upland Transition Zone	44 - 52	33 - 44	66 - 81	44 - 55	
Annual Average of all Sources yd^3/yr[18]	*20,900*	*42,000*	*15,200*	*25,700*	
Percent Anthropogenic Sediment Sources Entire Watershed	*36 – 43*	*16 – 21*	*36 – 44*	*25 - 32*	

7.0 Conclusions

The bank erosion, road sediment, and landslide analyses and sediment budget results (Tables 8 and 9) suggest the following:

1. The partial list of sediment sources quantified in this report accounts for the majority, 68 to 78 percent, of estimated sediment exiting the Deschutes River as defined by dredging and bathymetric records of Capitol Lake during the 31 years from 1972 to 2003.

[14] This report; low estimate is road-related landslides only, high estimate assumes all landslides are land-use related.
[15] Sullivan et al. (1987); used 1900 tonnes/yr estimate for peak road construction years 1975-1978 & 1.5 bulk density
[16] Sullivan et al. (1987); current (1987) annual estimate extrapolated to 10 yr period of 1981-1991
[17] This report; average of annual range extrapolated to 12 yr period of 1991-2003 bank erosion analysis
[18] From Table 8

2. Sediment input to the Deschutes River is dominated by fines estimated at 76 percent of the total.

3. Erosion of glacial terrace banks is the dominate source of fine and coarse sediment, accounting for two thirds of all fines in the 31-year analysis period and roughly half of the annual averaged sediment accumulation in Capitol Lake. Erosion of glacial terraces increased significantly during the period including the January 1990 storm of record. Increases in glacial terrace erosion in the mainstem correspond to increases in landsliding in the headwaters primarily associated with forest roads and the peak flow of record in January 1990.

4. During the 1981 to 1991 period, estimates of net sediment influx exceeded export, indicating an increase in channel stored sediment. Only the 1981 to 1991 time period shows a net increase in channel stored sediment, which can be explained by the flood of record in January of 1990 that resulted in large increases in landsliding in the upper basin and glacial terrace erosion.

5. An overall net decrease in channel stored sediment could represent a number of source accounting or estimate errors, such as: sediment from unquantified sources such as bank erosion in the tributaries, an underestimation of sediment from quantified sources, a deficit in channel-stored sediment, an overestimation of sediment accumulation, and/or differences in bulk density assignments in converting sediment yield. Annual sediment discharge values based on sediment accumulation in Capitol Lake vary by 20,000 m^3, and part if not all of the channel storage deficit could be accounted for in the range of reported annual sediment volumes. The potential for net channel incision also exists and would be consistent with a loss of in-channel wood available for sediment storage and an increase in bank armoring over time.

6. The largest rate of sediment accumulation in Capitol Lake occurs from 1974 to 1983 and does not correspond to a commensurate increase in sediment input during that time or the previous time period. Possible explanations in addition to measurement or estimate errors are channel degradation from a localized change in bed control, such as removal of one or more channel-spanning log jams, release of sediment stored in beaver dams in Spurgeon Creek, or construction activity. Any systemic channel degradation or incision is unlikely due to the static base level control at Tumwater Falls and the alluvial nature of the study reach; however, increasing bank armoring may contribute to net scour locally.

7. Based on the revised landslide inventory and estimates of road surface erosion, roads and landslides may account for much of the suspended sediment in the upper watershed passing the 1000 Road as measured by Sullivan et al. (1987) and estimated by Collins (1994).

8. Overall, anthropogenic sources account for 26 to 32 percent of fine sediment from the major sediment sources quantified. Anthropogenic sources account for similar percentages of all sediment influx in the first and third analysis periods (Table 9). The percentage drops to less than 20 percent in the middle period during which time occurred the largest inputs of

sediment from glacial terrace bank erosion associated with the peakflow of record. Anthropogenic sources may contribute up to 50 percent of the sediment influx in the upper watershed.

9. Bank erosion rates calculated by valley length measured down the center of the Deschutes River floodplain as defined by Williams (1976) produced a pattern of erosion consistent between three geomorphic areas and time intervals (Figure 11). Although results vary by time period, bank erosion per unit valley length is essentially equal in the upstream and downstream areas and three to four times greater than in the prairie area.

Floodplain Sediment

A summary of channel-floodplain dynamics can be drawn from the data generated from the analyses in this report. Erosion of the floodplain has been fairly consistent between 1981 and 2003 (Table 10). Floodplain erosion in the 1972-1981 period, however, is a third lower although the third and fourth peak flows of record occurred during that time, and this rate may represent a static or low average estimate of floodplain erosion. The higher rate of floodplain erosion since 1981 is linked to sediment influx as a result of the 1990 flood of record included in the 1981-1991 period, and the subsequent transport of that sediment downstream during the 1991-2003 period. Those same sediments are not necessarily transported through the entire channel system during that time, but are exchanged in floodplain storage.

Table 10. Summary of floodplain erosion volumes and rates over the bank erosion analysis period of 1972 to 2003.

	Sediment (yd^3)			
Floodplain erosion	1972-1981[19]	1981-1991[20]	1991-2003[21]	1972-2003 (31 yrs)
Fines	254,600	432,000	566,600	1,253,00
Coarse	69,200	104,000	77,400	251,00
Total	323,800	536,000	644,000	1,504,000
Annual Average yd^3/yr	*36,000*	*54,000*	*54,000*	*48,500*
~Net Change in Channel Storage (yd^3/yr)[22]	-34,000	+7,000	-14,000	-7,000 to -12,000

An average rate of floodplain turnover, or average erosion return interval, was estimated from the area of mainstem 100-year floodplain less the active channel area divided by the annual area of floodplain bank erosion (Figure 15). The area of the mainstem floodplain was calculated from FEMA Q3 Flood Data for Thurston County modified to exclude adjacent low lying tributary floodplains. The area in floodplain for the recessional sand/kettle, glacial drift prairie, and upland transition areas is 1,430 acres (580 hectares), 1,500 acres (600 hectares), and 350 acres (140 hectares) respectively. The modified floodplain area is represented in Figures E-1 to E-3.

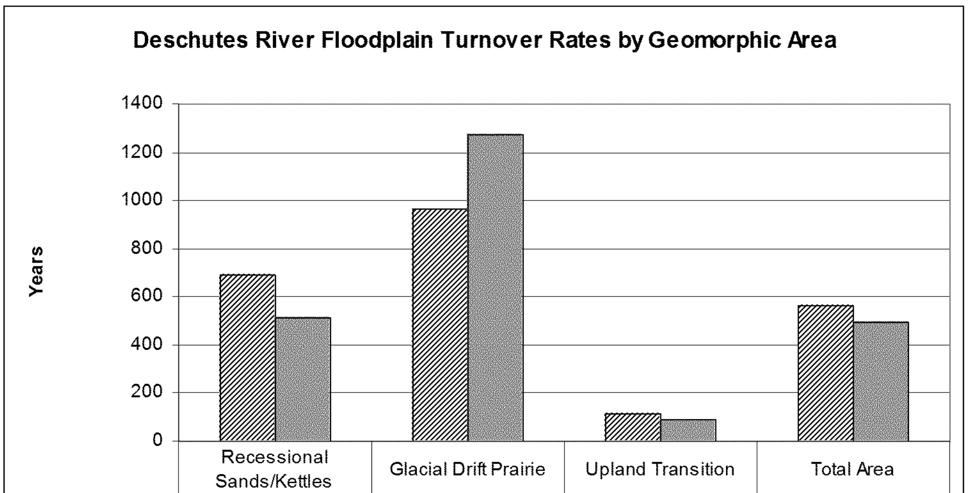
[19] Collins (1994) from Table A-4 pre-rounded inventory data
[20] Collins (1994) from Table A-3 pre-rounded inventory data
[21] This report
[22] Table 8

Floodplain turnover rates are generalized over the three geomorphic reaches and all floodplain elevations and averaged over a relatively short period of time.

Although bank erosion is fairly equal by volume between the upland transition and kettle areas (Figure 11), floodplain erosion rates are quite different between the two. Because of the smaller floodplain area in the upland transition zone, floodplain turnover is on the order of 100 years versus > 500 years in the lower kettle area. As it will take less time for the river to migrate across or erode its floodplain in the upper watershed, floodplain vegetation there would be expected to be no older than 100 years on average.

The floodplain turnover rate of approximately 1000 years in the glacial drift prairie area reflects the lack of sediment source areas found in both the upper transition and lower kettle areas. It also suggests a steady-state transport of sediment from the upper watershed through the prairie area. Sediment storage behind a natural constriction at the downstream end of the upper transition area helps to buffer the rate of sediment transport into the glacial drift prairie area.

The floodplain turnover rate in the kettle/sand area is intermediate between the two upstream areas. Total erosion is similar, but the larger floodplain in the kettle area produces longer floodplain sediment residence times simply by the math. The peak flows will also spread out over a greater floodplain area than upstream, reducing the flood height and concentration of flow. Another factor affecting floodplain erosion is a higher percentage of bank armoring in the kettle area, which may have reduced the area in bank erosion during the relatively short period of this analysis.



	Recessional Sands/Kettles	Glacial Drift Prairie	Upland Transition	Total Area
1981-1991	692	964	112	561
1991-2003	515	1271	91	494

Figure 15. Estimate of floodplain turnover in years for three geomorphic areas of the Deschutes River mainstem.

8.0 Future Bank Erosion Estimates

Conceptually, LiDAR comparisons should provide better estimates of bank erosion and channel adjustments over time than the current and past methods, although this claim has not yet been demonstrated. We can anticipate an improvement in the potentially large and poorly defined measurement errors associated with the current and past methods (Collins 1994), particularly as LiDAR data collection, post-processing and algorithms improve. Three-dimensional comparison of sequential ground-penetrating LiDAR images should reveal patterns and yield volumes of erosion and depositional area (areas of net loss or gain of bank and bed material) along the mainstem channel and likely introduce no more error than the current methods. Water level or stage should ideally be similar between LiDAR flights or a correction factor must be developed to adjust for differences in water level reflected in the images. As recommended in Cramer (1997), the installation of permanent cross-sections could provide important reference controls for whatever methods are used to update this work in the future.

Where bed load movement and predictions of future channel migration and erosion locations may be of interest, several available analytical techniques could be used. Ham and Church (2000) used a technique similar to what sequential LiDAR could produce by employing an analytical stereoplotter, aerial photographs, and a sediment budget approach to estimate bed-material transport along reaches of the Chilliwack River in British Columbia. The Ham and Church (2000) morphologic approach would provide an estimate of fluvial bedload transport independent of poorly-predictive hydraulic equations and upstream sediment input and routing assumptions, which could be used to predict future areas of channel migration. LiDAR imagining could greatly facilitate using the Ham and Church (2000) approach. Beechie (2001) has also developed a simple relationship based on channel width to predict annual travel distance of bed load sediment useful for identifying reaches that may take longer to recover from large, short-term increases in sediment supply, and Lagasse et. al. (2004) developed an empirical method for identifying river reaches with the highest erosion rates based on sinuosity and channel width.

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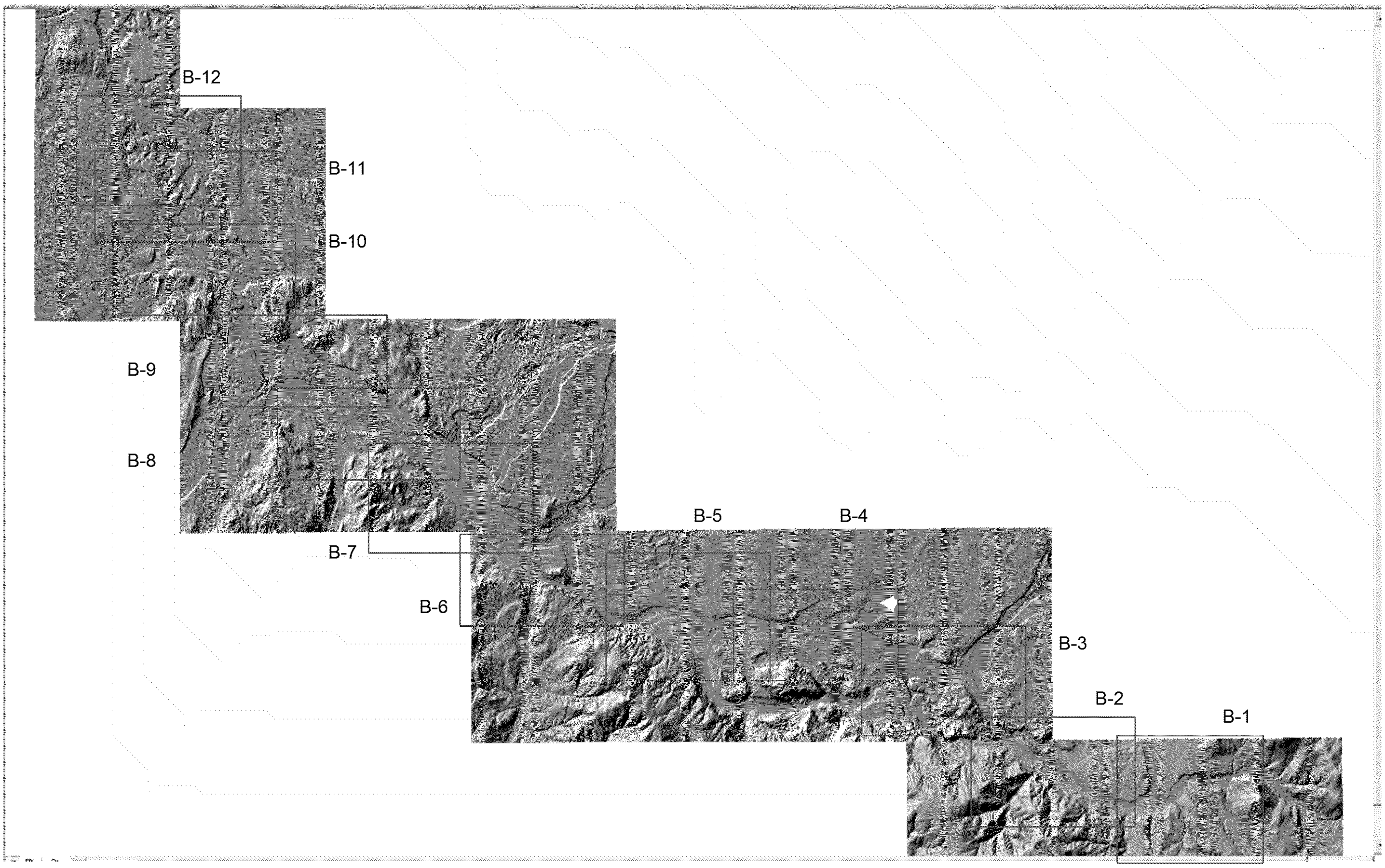
APPENDIX A

1991 to 2003 Deschutes River Mainstem Bank Erosion Inventory Data

APPENDIX B

1991 to 2003 Deschutes River Mainstem Erosion Sites

Index to Erosion Site Figures



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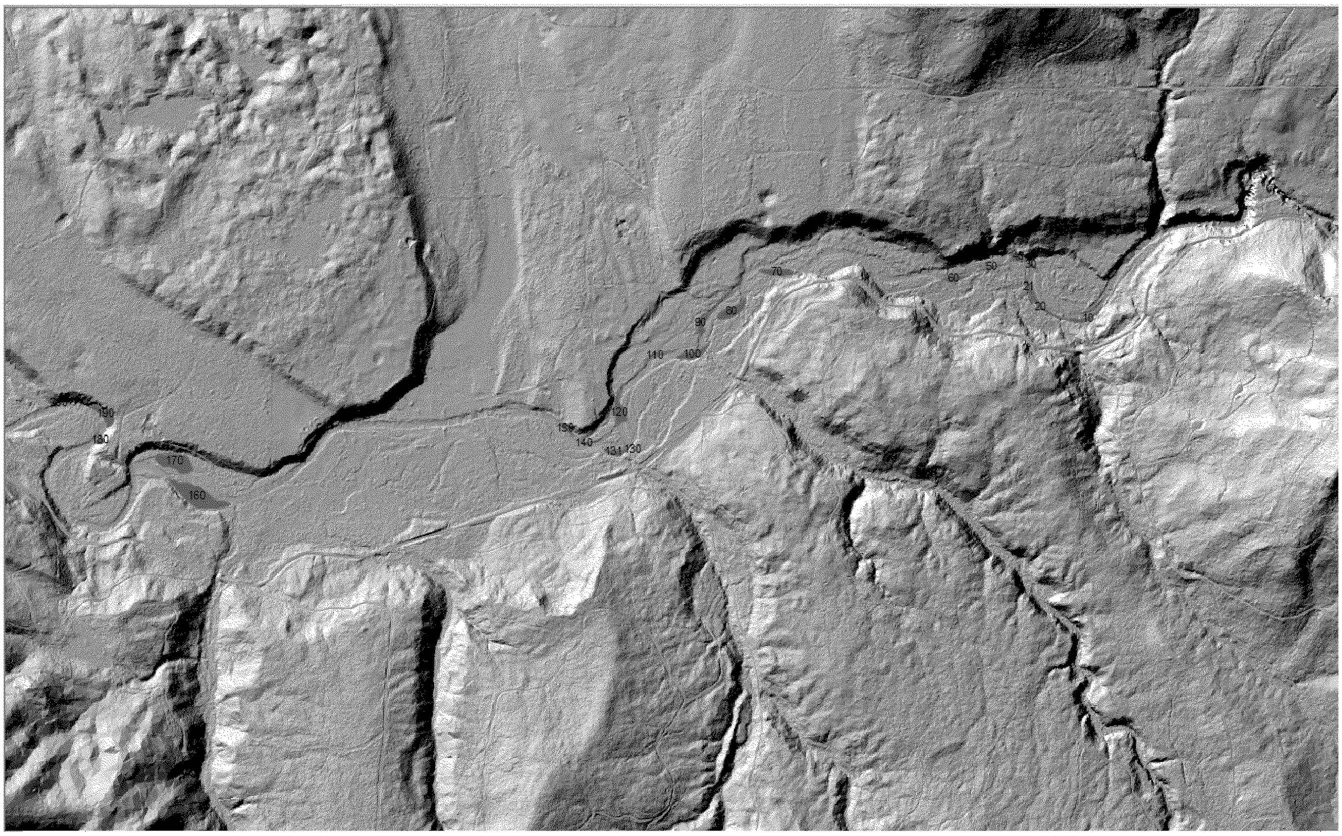

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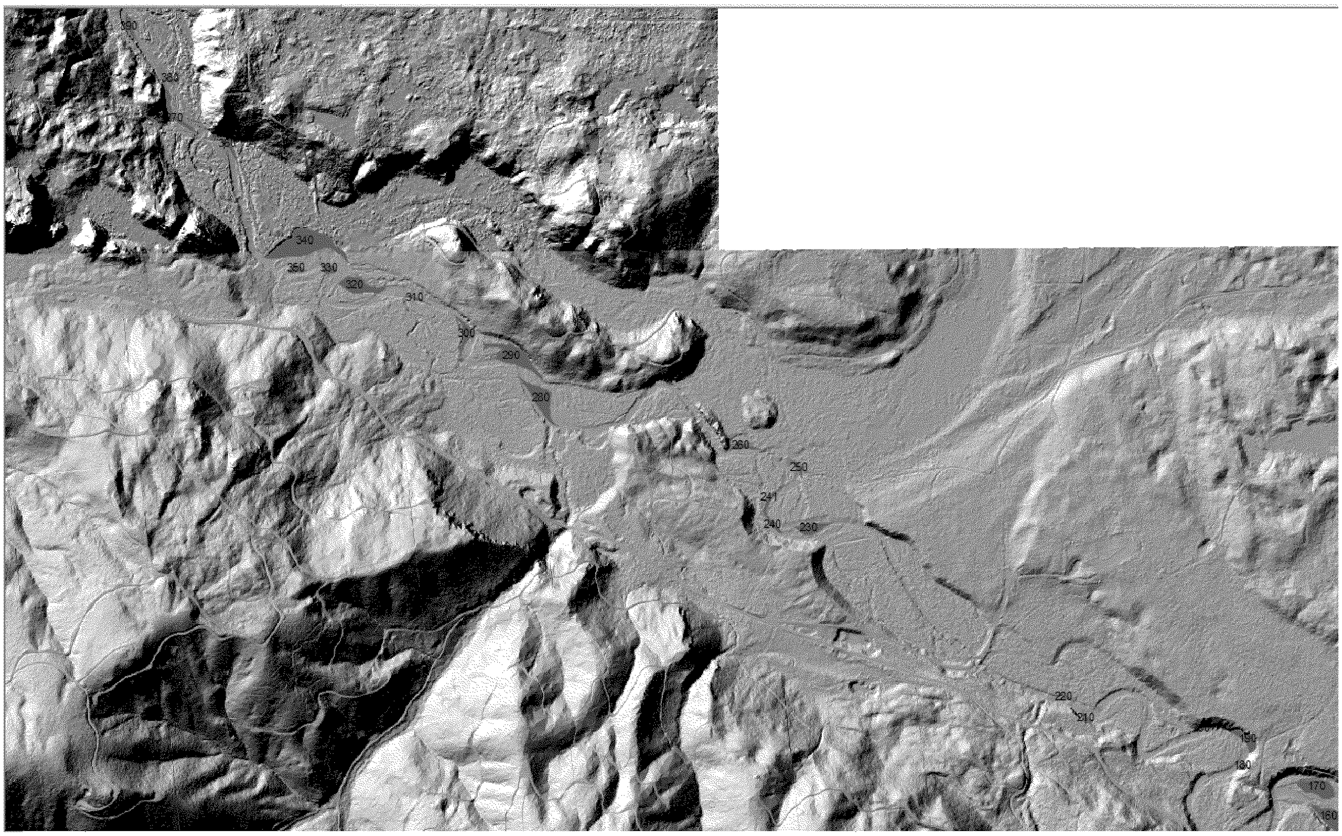
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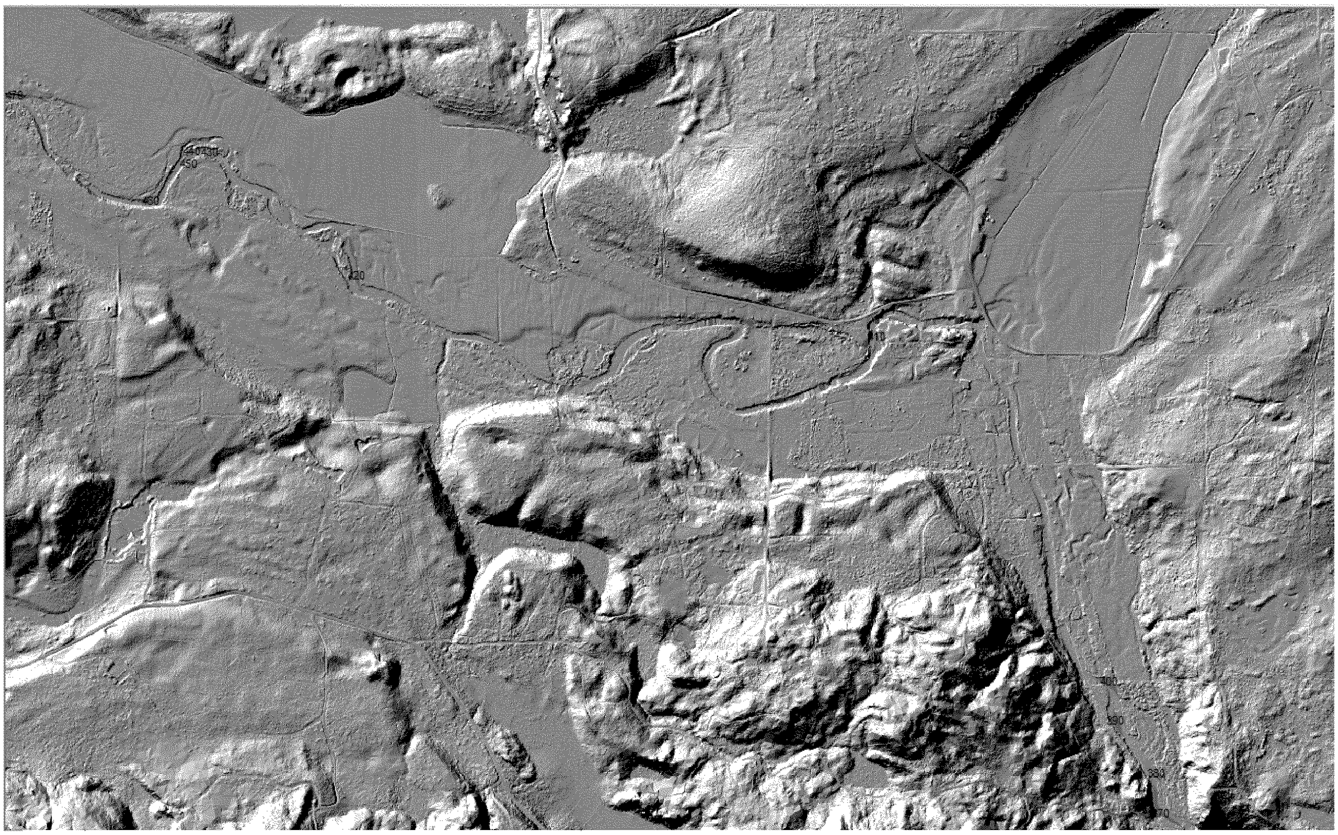

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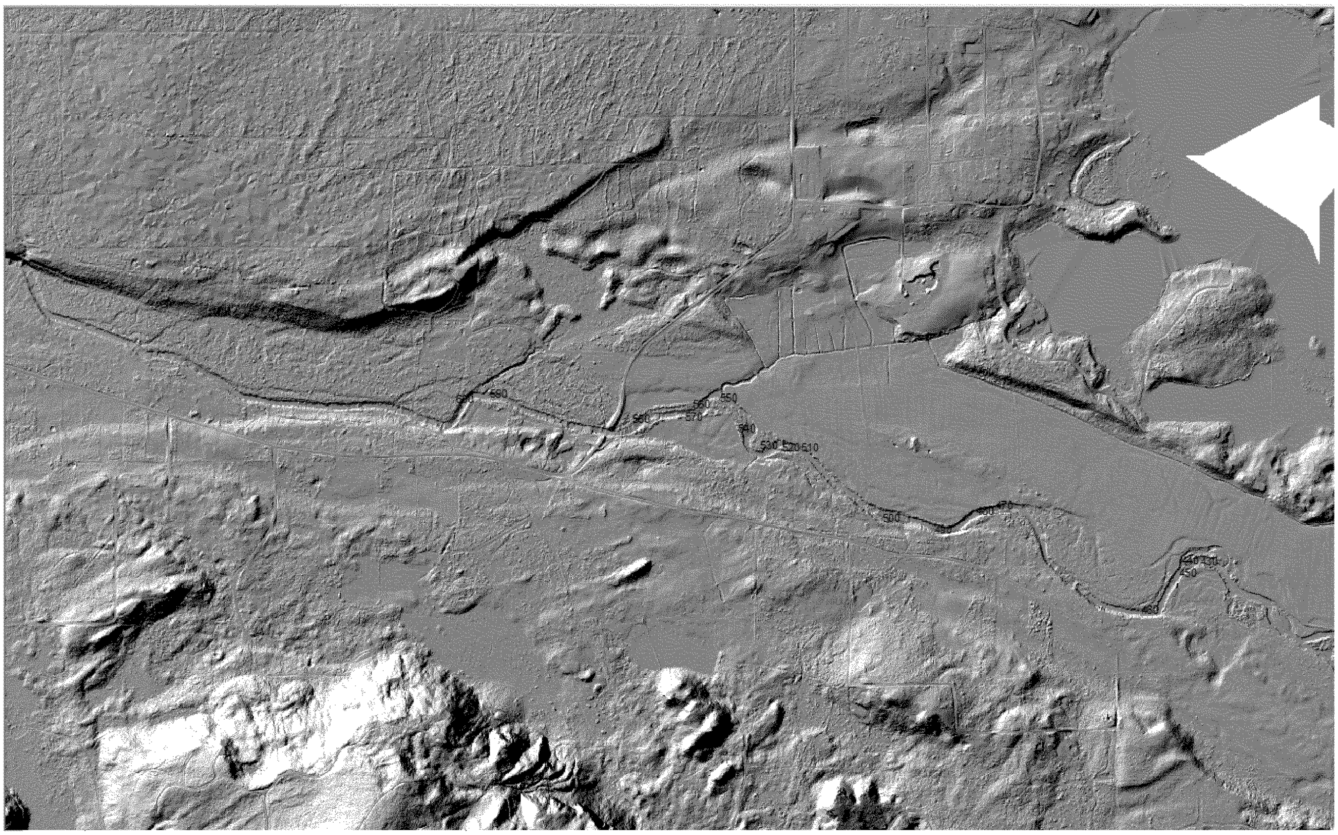

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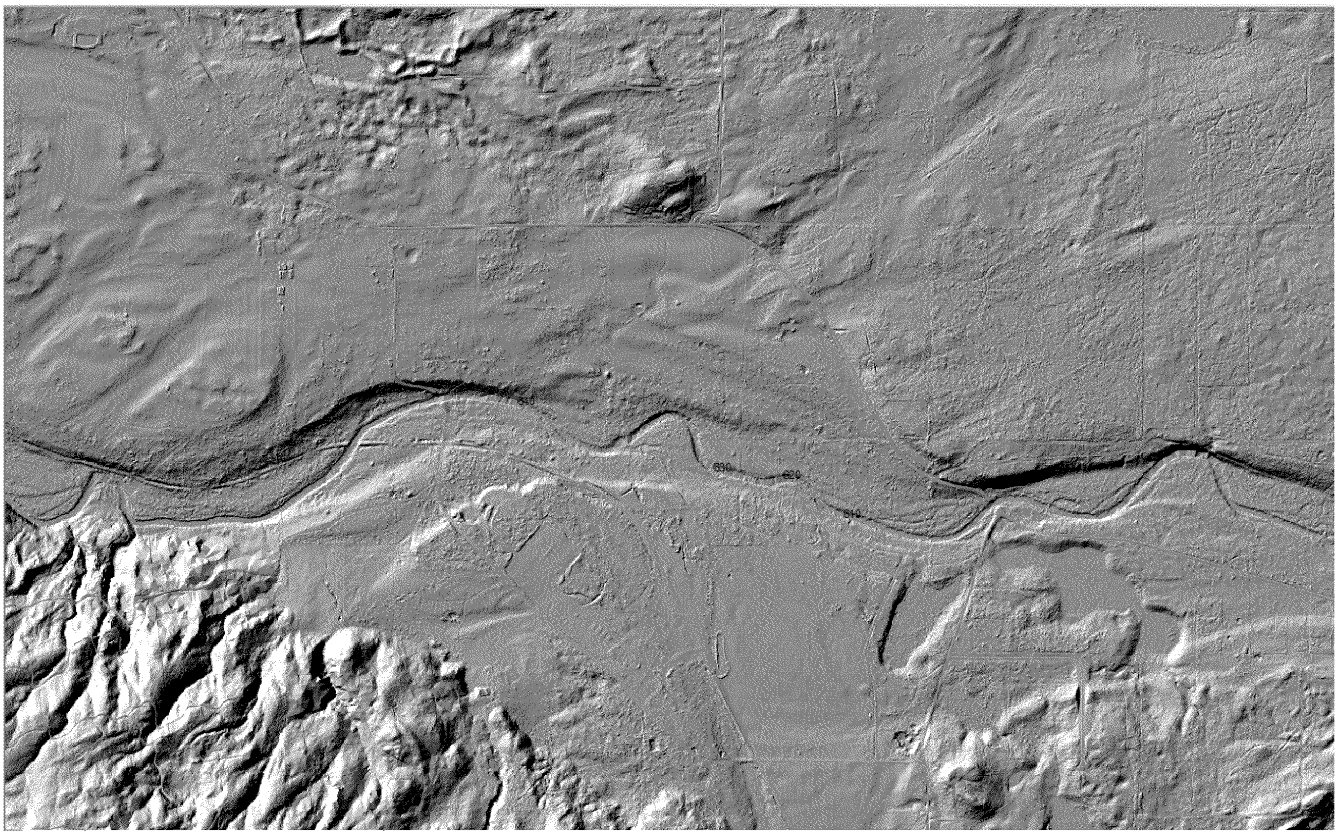

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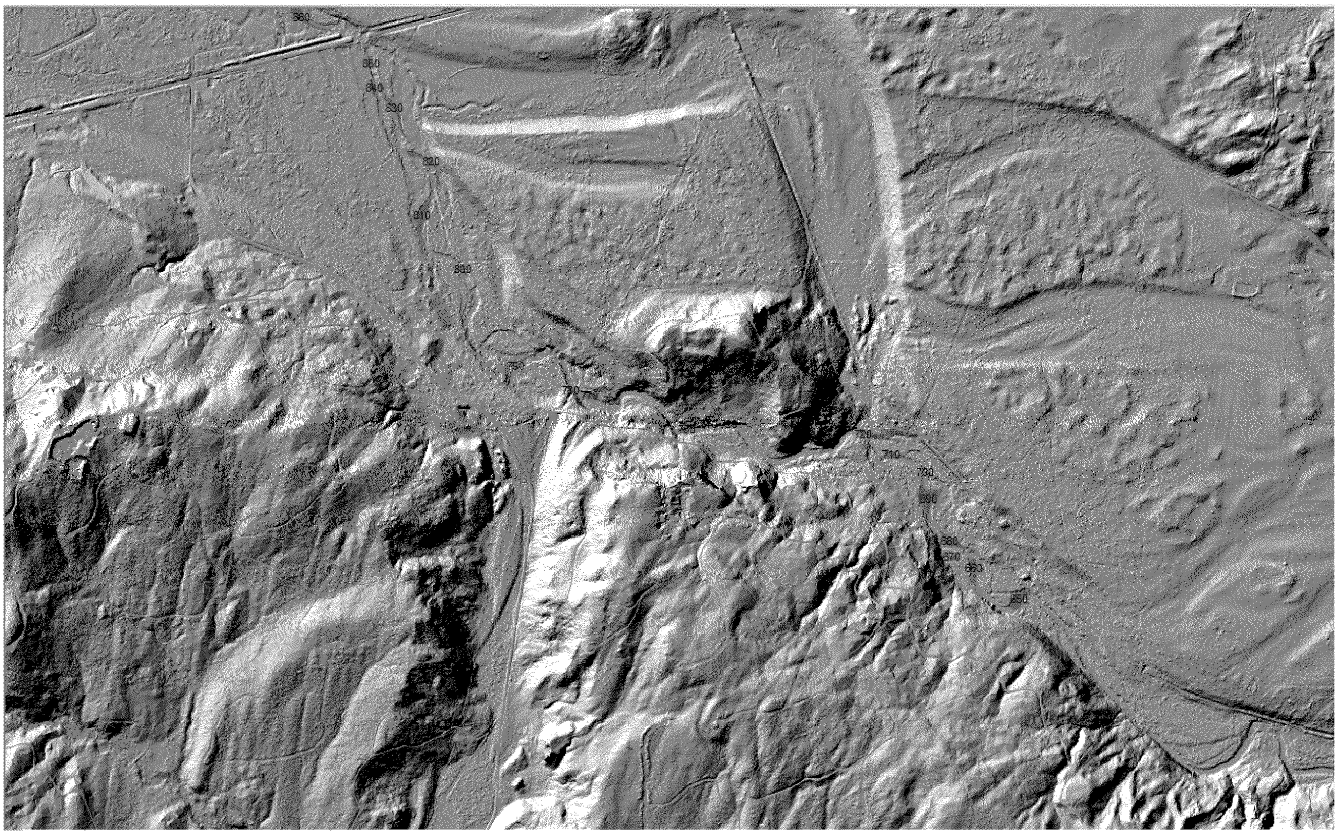

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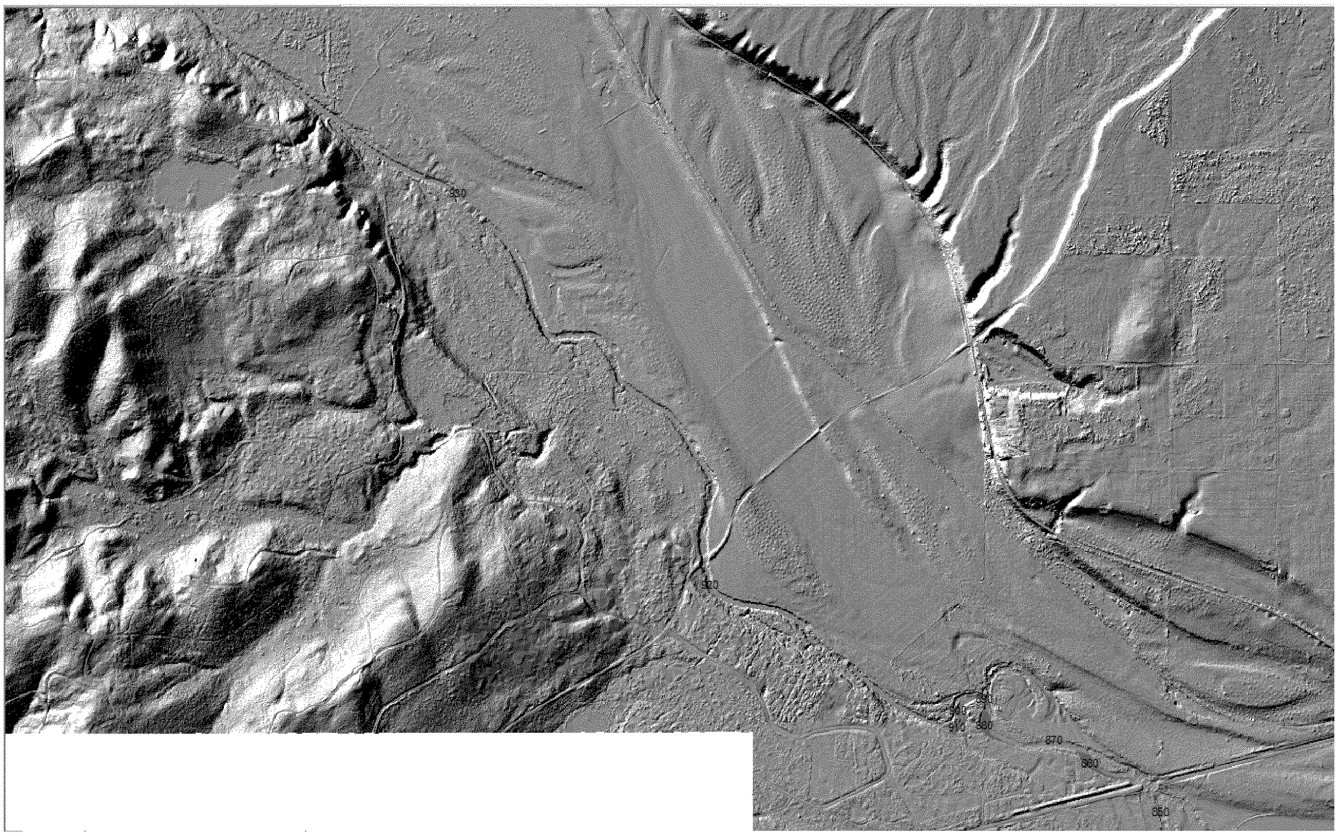

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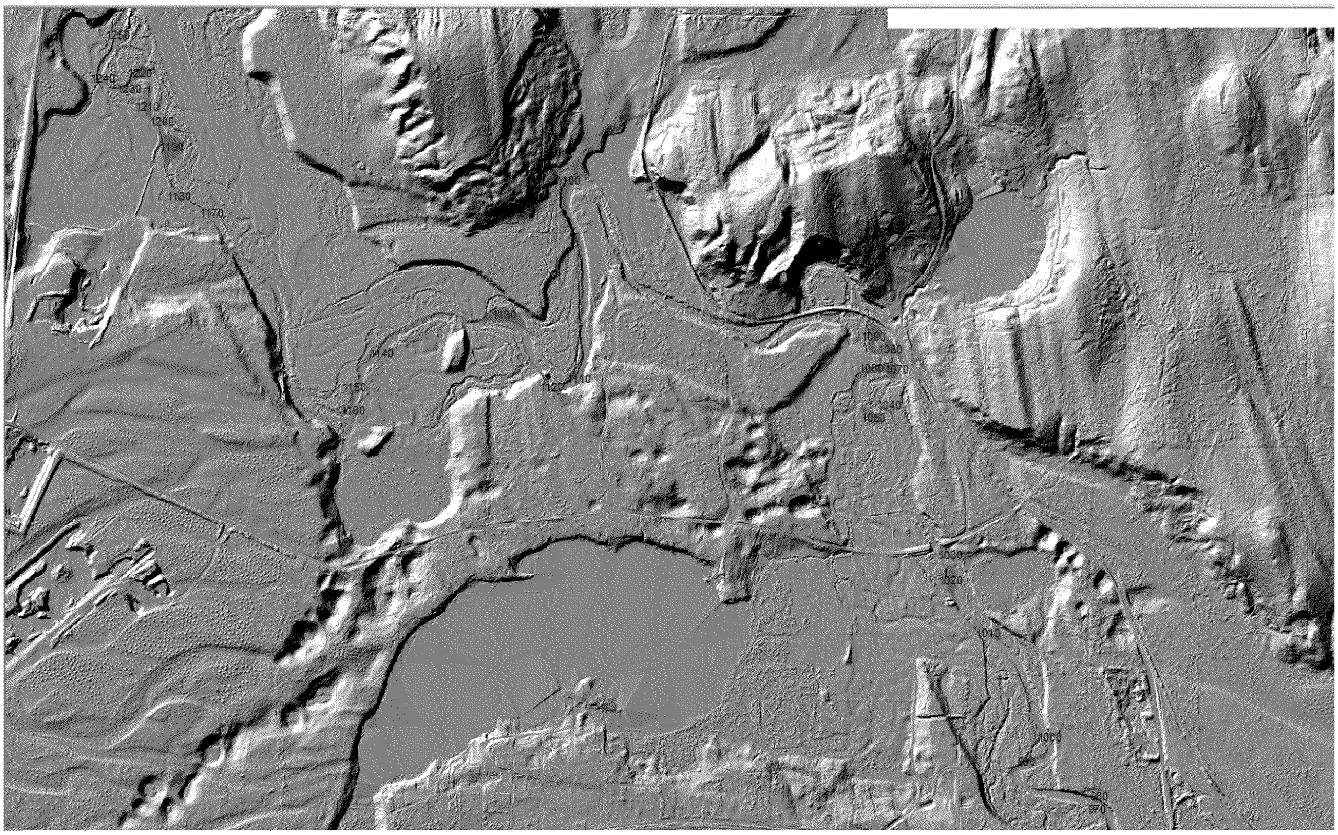

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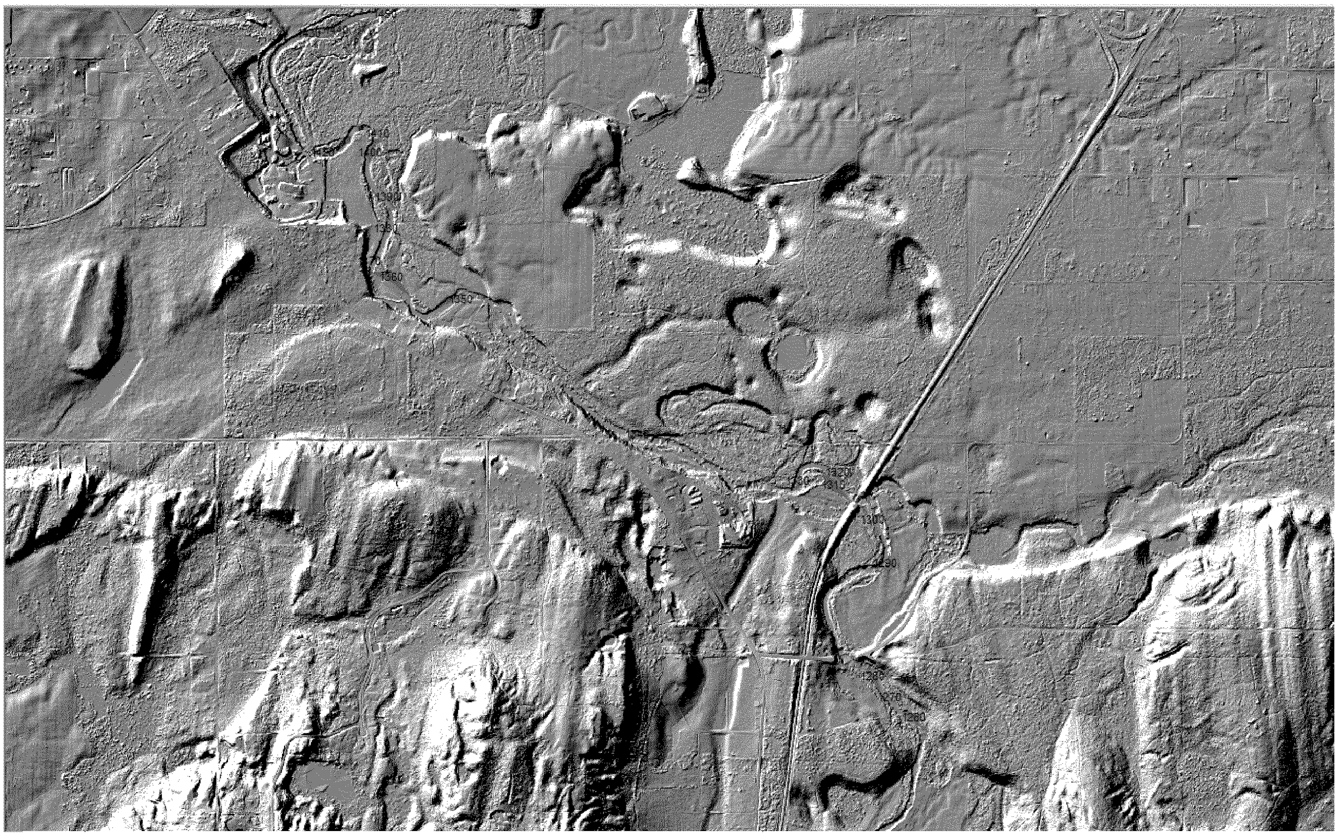

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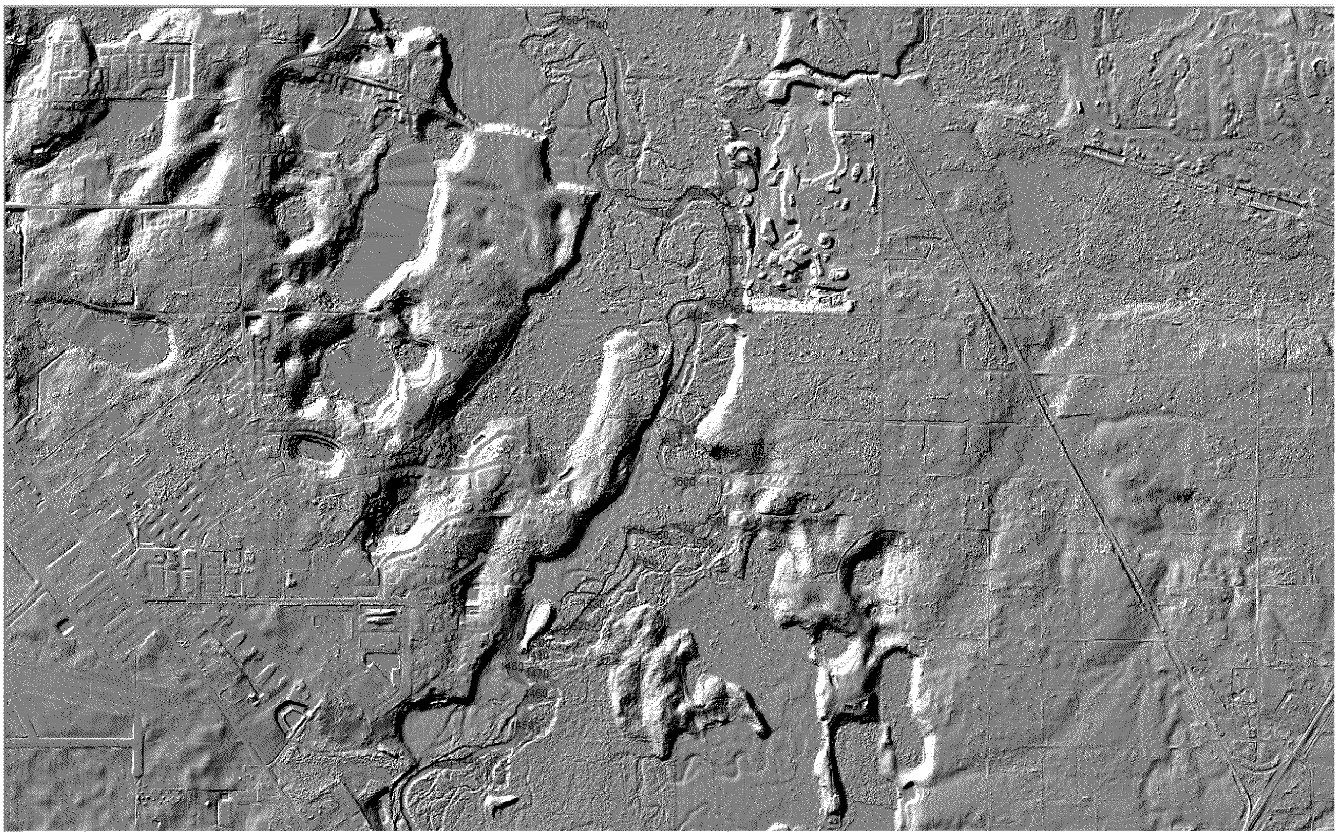

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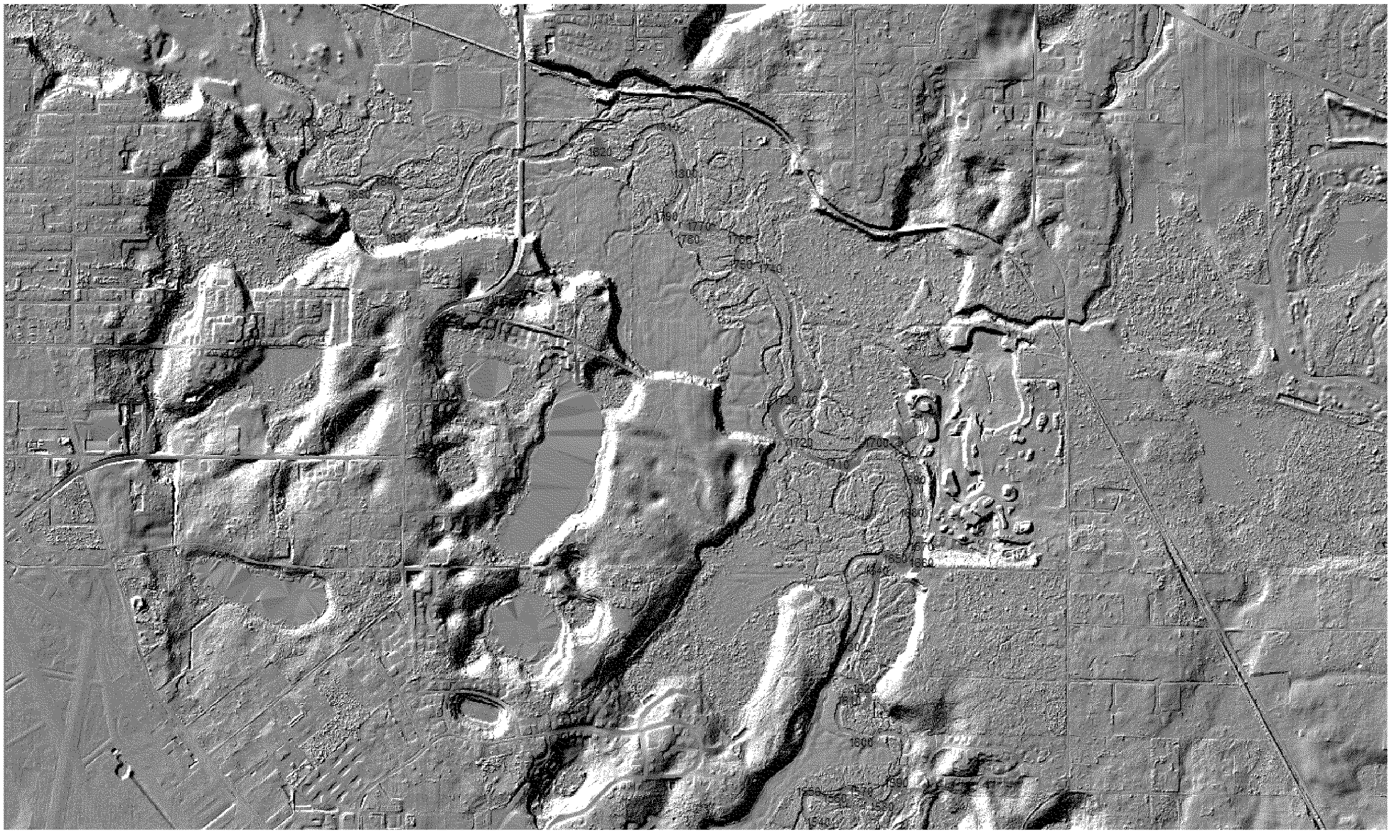

APPENDIX C

Upper Deschutes River Basin Landslide Provisional Landslide Inventory and Map

SLIDE	YEAR	Slide type	Total delivered sediment (cu. m)	Delivered sediment (yd3) *	Land Use Type	Terrain unit *	Soil Unit *	Comments *
1	66	DF	273	356	N	wb	?	
2	66	DF	256	334	R	wb	?	
3	66	SR	0	0	N	wb		Not on map
4	66	DF	2075	2714	N	wb	198	
5	66	DF	903	1181	N	wb	10	
6	66	DFq	875	1145	N	wb		DF track opposite #5 on map per Turner
7	66	DF	934	1222	N	wb	96	
8	66	SR	1650	2158	N	wb	82	
9	66	SR	688	900	R	wb	83	
10	66	SR	316	414	N	wb	231	
11	66	LPD				wb	231	Assume feature predates inventory or del. volume for time period not yet calculated
12	66	SSD	364	477		wb	200	
13	66	DF	548	716		wb	197	
14	66	DF	596	780	N	wb	106	
15	66	SR	79	104	R	wb	231	
16	66	LPD			N	wb	231	Assume feature predates inventory or del. volume for time period not yet calculated
17	66	SR	0	0	R	wb		Not on map
18	66	SR	0	0	R	wb		Not on map
19	66	DF	457	597	R	wb	10	
20	66	SR	216	282	R	wb	81	
21	66	SR	416	544	R	wb	96	
22	66	SR	416	544	N	wb	63	
23	66	SR			R	gt	108	No assigned volume; assume no delivery from position on slope (Raines)
24	66	SSD	No del.		N	gt	50	
25	66	DF	618	808	N	dv	161	
26	66	DF	735	962	N	wb	161	
27	66	DF	1621	2120	N	wb	106	
28	66	LPD				wb	231	Assume feature predates inventory or del. volume for time period not yet calculated
29	66	DF	416	545	N	wb	230	

30	66	LPD				gt	62	Assume feature predates inventory or del. volume for time period not yet calculated
31	66	LPD				gt	63	Assume feature predates inventory or del. volume for time period not yet calculated
32	66	LPD				gt	63	Assume feature predates inventory or del. volume for time period not yet calculated
33	66	SR	1259	1647	R	wb	80	
34	66	DF	607	794	N	wb	160	
35	66	SR			N	wb	198	No assigned volume; assume no delivery from position on slope (Raines)
36	66	LPD				wb	231	Assume feature predates inventory or del. volume for time period not yet calculated
100	70	SR	1041	1361	N	gt		DUPLICATE WITH BANK EROSION
101	70	SR	918	1201	N	gt	8	
102	70	SR	1007	1317	R	gt	80	
103	70	SR	409	536	R	wb	6	
104	70	SR	834	1091	N	dv	219	
105	70	SSD	1249	1633		gt	63	
200	78	SR	1549	2026	R	wb	106	
201	78	SR	131	171	R	gt		
202	78	SR	2085	2726	R	gt	108	
203	78	SR	1232	1611	R	wb	124	
204	78	SR	342	447	N	gt	63	
205	78	SR	548	717	N	gt	63	
206	78	SR	443	579	R	wb	231	
207	78	DF	5020	6566	N	wb	96	Changed from SR to DF as feature includes slide track former #232 per Turner
208	78	SR			N	wb	96	Appears to deliver but no volume assigned (Raines)
209	78	SR	694	908	N	wb	?	
210	78	SR			R	wb	6	No assigned volume; assume no delivery from position on slope (Raines)
211	78	SR	855	1119	R	wb	161	
212	78	SR	1525	1995	R	wb	197	
213	78	SR	717	937	R	wb	56	

214					R	wb	198	Road sidecast delivered vol not included in landslide inventory per Turner
215	78	SR	1258	1645	R	wb	7	
216	78	YAR DING	3779	4942	R	wb	7	
217	78	DF	673	881	R	wb	198	
218	78	DF	1420	1857	R	wb	161	
219	78	SR	579	757	R	wb	160	
220	78	SR	3804	4975	R	wb	161	
221	78	DF	772	1009	N	gt	95	
222	78	DF	2045	2675	R	wb		Slide & DF r bank trib below 801
223	78	SR	2556	3343	R	wb	197	No soil unit number in polygon
224	78	LPD				wb	6	Assume feature predates inventory or del. volume for time period not yet calculated
225					R	dv	160	Road sidecast delivered vol not included in landslide inventory per Turner
226					R	dv	160	Road sidecast delivered vol not included in landslide inventory per Turner
227	78	SR	3304	4321	R	wb	161	
228	78	SR	3180	4160	R	dv	161	
229	78	DF	1065	1393	R	wb	129	
230	78	SR	1259	1647	R	wb	161	
231	78	DF	5147	6733	R	wb	106	
232					RECHE CK PHOTO	wb		Changed to slide track of #207
233	78	DF	443	580	N	gt	13	
234	78	SR	140	183	R	gt	63	
300	83	LPD			R	gt	80	Assume feature predates inventory or del. volume for time period not yet calculated
301	83	SR			R	gt	91	No assigned volume; assume no delivery from position on slope (Raines)
302	83	DF	1416	1852	R	wb	197	
303	83	SR	1413	1848	R	wb	197	No soil unit number in polygon
304	83		0		R	wb		Road sidecast assoc w/slide 225 per Turner; delivered vol not in slide inventory
305	83	DF	1857	2429	R	dv	161	Lower Ware Ck DF off 3412 road
306	83	DF	3617	4731	R	dv	160	

307	83	SR	1200	1569	R	wb	161	
308	83	SR	251	328	R	wb	161	
309	83	LPD				gt	9	Assume feature predates inventory or del. volume for time period not yet calculated
310	83	LPD				wb	9	Assume feature predates inventory or del. volume for time period not yet calculated
311	83	SR	1644	2150	N	wb	160	
312	83	SR	2043	2673	R	wb	161	
313	83	DF	3303	4321	R	wb	161	
314	83	DF	1855	2426	R	wb	161	Mid Ware Ck DF below slide 230
315	83	DF	0	0	N	wb		Not on map
400	87	LPD				wb	160	Assume feature predates inventory or del. volume for time period not yet calculated
401	87	SR	1167	1527	R	wb	160	
402					R	wb		Road sidecast delivered vol not included in landslide inventory per Turner
403	87	DF	2324	3040	R	wb	160	
404	87	LPD				wb	105	Assume feature predates inventory or del. volume for time period not yet calculated
405	87	DF	1888	2470	R	wb	197	
406	87	SR	63	82	N	wb	160	
407	87	SSD	No del.		R	wb	215	
408	87	DF	2300	3008	N	wb	200	SR/DF start of slide complex 601/602/704
409	87	DF	520	680	N	wb	200	
						wb	91	
500	90	SR	373	488	N	wb	160	
501	90	SR	174	227	N	wb	7	
502	90	SR	1516	1983	N	wb	56	
503	90	SR	1363	1782	R	wb	7	
504	90	DF	3568	4667	R	wb	197	
505	1990	DF	3950	5166	N	wb		Upper Ware Ck DF
506	90	SR			R	wb		Unnumbered slide immed. west of 305 in Ware Ck; assume no del as track doesn't connect with stream below
507	90	DF	814	1064	R	wb	161	
508	90	SR	783	1024	R	wb	10	
509	90	SR	599	783	R	wb	159	

510	90	DF	361	472	N	wb	159	
511	90	DF	1650	2158	R	wb	200	
512	90	DF	800	1046	N	wb	160	
513	90	DF	1115	1458	R	wb		
514	90	SR			R	wb	160	No assigned volume; assume no delivery from position on slope (Raines)
515	90	DF	811	1060	N	dv	160	
516	90	DF	700	916	R	dv	160	
517	90	DF	7440	9731	R	wb	105	
518	90	SR	3504	4583	N	wb	160	
519	90	SR	1924	2516	N	wb	105	
520	90	LPD				gt	63	Assume feature predates inventory or del. volume for time period not yet calculated
521	90	LPD				gt	63	Assume feature predates inventory or del. volume for time period not yet calculated
522	90	DF	1120	1465	N	wb	10	
523	90	SSD	No del.		R	gt	90	
524	90	SR	1848	2417	R	dv	160	
525	90	LPD				gt	63	Assume feature predates inventory or del. volume for time period not yet calculated
526	90	LPD				wb	10	Assume feature predates inventory or del. volume for time period not yet calculated
527	90	SSD	0	0		gt	91	No delivery
528	90	DF	9453	12364	R	wb	60	
529	90	SR	650	851	N	wb	63	Inner gorge failure on r bank opposite slide 205
530	90	SR	977	1278	N	gt	63	
531	90	SR	1089	1425	N	gt		DUPLICATE WITH BANK EROSION
532	90	SR	552	722	R	wb	165	
533	90	LPDq		0		wb	106	Questionable feature
534	90	DF	586	767	N	wb	160	
535	90	SR			R	wb	197	No assigned volume; assume no delivery from position on slope (Raines)
536	90	SR			N	wb		No assigned volume; assume no delivery from position on slope (Raines)
600					N	wb		Same slide as #534
601	93	LPD				wb	200	Part of slide complex 408/602/704; most mat'l still on slope

602	93	SR	1200	1570	N	wb	200	SR travels down 408 DF track; part of slide complex 408/601/704
603	93	LPD				wb	106	Assume feature predates inventory or del. volume for time period not yet calculated
700	99	LPD				wb	231	Assume feature predates inventory or del. volume for time period not yet calculated
701		SRq			N	wb		Questionable: poss yarding scar
702	99	SR	1216	1590	N	gt	63	
703	99	SR	171	224	R	wb	231	
704	99	SSD	0	0	R	wb	200	Assoc w/slide complex 408/601/602; mat'l still on slope
705	99	SSD	419	548	N	gt		
706	99	DF	495	647	N	wb	160	DF assoc w/SSD sed still on slope
707	99	DF	2120	2773	R	wb	10	
708	99	SSD	15630	20444	R	wb	161	
709	99	SR	811	1060	N	wb	161	
710	99	DF	1041	1362	N	wb	161	
711	99	SR			R	wb	56	No assigned volume; assume no delivery from position on slope (Raines)
712	99	DF	3190	4172	R	wb	10	
713	99	DF	2629	3439	N	gt	124	
714	99	SSD	1211	1583	N	gt	62	
715						dv	160	J. Ward slide? On map but not inventory
716						dv	160	J. Ward slide? On map but not inventory
800	2001	SR	761	995	N	wb	197	
801	2001	SR	630	824	N	wb	56	
1000						wb	161	On map but not inventory

Slide Type:

SR	Shallow rapid
DF	Debris flow
SSD	Small sporadic deep-seated
LPD	Large persistent deep-seated

Land Use Type:

N	Non-road
R	Road
*	Data or information added by Raines
408	Assume 2 failure compartments below 602 feature of 145x90x3 ft and 425x50x2 ft
602	Assume half of failure volume of 133x160x4 ft is still on slope
gt	glaciated terrain
dv	headwaters terrain
wb	weathered bedrock

June 4 2007 Ted Turner identified slides no. 6 and 533 as questionable

APPENDIX D

Road Sediment Modeling Methods

Methods for Estimating Road Surface Erosion

The Washington Road Surface Erosion Model or WARSEM (Dubé et al. 2004), a recent revision of an empirical road surface erosion model found in the Washington Forest Practices Board Standard Methodology for Conducting Watershed Analysis (1997), was used to estimate surface erosion from unpaved roads. The screening Level 1 application of the model was used for this analysis, which allows user input of some road attributes appropriate to the level of data derived from GIS and air photo analyses.

Road, stream, and geology data for the Deschutes River basin available as GIS layers were acquired from the Department of Natural Resources. Unpaved roads were identified from aerial photographs augmented by a printed Weyerhauser transportation map for that ownership (Figure x). Data generated by GIS to input into the model included length of road connected to streams in two connectivity classes (Figure x), two road classes that reflect traffic levels, and three geologic erosion factors. Two model runs were made by varying road surface conditions to help bracket potential erosion estimates.

Since no field data were collected, a number of simplifying assumptions about road conditions were made that are summarized below. Table C-2 details the results of a GIS analysis of road classes by delivery and geology that was used in model. Table C-1 is followed by WARSEM-generated summary reports for each model run and a detail report on model input data and results for each road class and delivery category by model run. Model run 1 was conducted for the gravel surfacing and run 2 is the gravel with ruts surfacing model run. Length and width values in the WARSEM reports are in units of feet, and total sediment is in units of tons per year.

Model Input Data and Assumptions

1. Understanding the degree to which roads are connected to streams is fundamental to estimating sediment delivery to streams from roads. The model assumes 100 percent delivery of sediment for those road segments directly connected to a stream, and partial delivery of road sediment of 35 and 10 percent if the road is within 100 and 200 feet of the stream. The length of unpaved roads directly connected to the stream system was estimated by calculating the length of roads 250 feet either side of a stream crossing, a common default value used in earlier versions of the road sediment model. The length of unpaved road with partial delivery was estimated by measuring the length of road falling within a 200 foot buffer of a stream excluding the direct connectivity segments at road crossings.

2. The easily identified main haul roads were coded separately from the remainder of the unpaved roads, as frequent log haul traffic significantly affects sediment production and is reflected in the model. All other unpaved roads were assumed to be secondary roads receiving light or daily car, pickup or recreational use (1 to 5 per day) and one or two log trucks which could also be interpreted as loaded dump trucks or other heavy commercial vehicle. The secondary road class fits the definition of many unpaved residential and light use logging roads, but not logging spur roads receiving only occasional traffic. Dividing model results for the secondary roads by a factor of two, the difference between the "light"

use and "occasional" use traffic categories in the model, helped to bracket the difference that more specific information on traffic use might make in modeled results.

3. The gradient of the main haul roads were conservatively assumed to be less than 5 percent and secondary roads as 5 to 10 percent.

4. All roads were assumed to be insloped rather than outsloped or crowned. Insloped roads are assumed to have an inboard ditch and the entire area of the running surface is factored into the erosion equation.

5. For this analysis, all roads were assumed to be older than 2 years for the 12-year erosion period. Newly constructed or rebuilt roads have a much higher erosion rate during the first year or two following construction; however, this level of detail was not available for this analysis.

6. Only sediment from the road running surface, which includes the ditch, was modeled as no data were available on height, length, and cover condition of the cutslope and fillslope portions of the road prism.

7. The model recognizes several categories of road surfacing that can have a large effect on sediment estimates. The categories and corresponding surfacing factors are in Table C-2. To bracket the potential effect of road surfacing on sediment estimates, all unpaved roads were assumed to be surfaced with gravel in either good condition for the first run of the model and gravel with ruts in the second run.

Table C-2. WARSEM road tread surfacing and factors (Dubé et al. 2004).

Surfacing Type	Surfacing Factor
Asphalt	0.03
Gravel	0.2
Gravel with ruts	0.4
Pitrun or worn gravel	0.5
Grassed native	0.5
Native surface	1
Native with ruts	2

8. A rainfall factor in the model derived from average annual rainfall data is assigned based on road segment location by township, range, and section. Since road lengths were summed across the basin in like categories of delivery, traffic, and geologic erosion rate for input into the model rather than entering the location of individual road segments, a single township/range/section value of T15N R3E S7 (main haul) or S27 (secondary roads) approximating the central area was used.

9. The lengths of delivering road segments were also calculated by length in each geologic unit within each road class, and then combined into one of three geologic erosion factors provided in the model (Table x).

Table C-2. Summary of road classes by geologic and delivery data.

Geologic Symbol	Geology Type	Length (miles)	WARSEM Geologic Erosion Factor	Delivery category	Road Class
Main haul road stream crossings					
Eva(n)	Andesite flows	4.852	1	directly to stream	main haul
Qgog	Outwash gravel	3.713	1	directly to stream	main haul
Qa	Alluvium	2.087	2	directly to stream	main haul
Qapo(lh)	Outwash deposits	0.054	2	directly to stream	main haul
		10.706			
Main haul roads w/in 200 feet of stream					
Eva(n)	Andesite flows	1.816	1	within 200 feet	main haul
Qgog	Outwash gravel	2.155	1	within 200 feet	main haul
Qapo(lh)	Outwash deposits	0.091	2	within 200 feet	main haul
Qa	Alluvium	1.095	2	within 200 feet	main haul
		5.157			
Non-main haul road stream crossings					
Eva(n)	Andesite flows	130.63	1	directly to stream	secondary
Evc	Volcaniclastics	1.952	1	directly to stream	secondary
Mvc(1)	Volcaniclastics	12.078	1	directly to stream	secondary
OEvba	Basalt flows	3.319	1	directly to stream	secondary
OEvc	Volcaniclastics	5.075	1	directly to stream	secondary
Qgog	Outwash gravel	6.79	1	directly to stream	secondary
Ec(2pg)	Continental sandstor	5.558	2	directly to stream	secondary
Qa	Alluvium	1.467	2	directly to stream	secondary
Qap(wh)	Drift	0.005	2	directly to stream	secondary
Qapo(lh)	Outwash deposits	1.74	2	directly to stream	secondary
Qls	Landslide deposits	1.936	2	directly to stream	secondary
Em(2m)	Marine sedimentary	0.829	5	directly to stream	secondary
Qgp	Drift	6.674	5	directly to stream	secondary
Qgt	Till	2.397	5	directly to stream	secondary
		180.45			
Non-main haul roads w/in 200 feet of stream					
Eva(n)	Andesite flows	145.822	1	within 200 feet	secondary
Evc	Volcaniclastics	4.721	1	within 200 feet	secondary
MOigb	Gabbro	0.156	1	within 200 feet	secondary
Mvba(1)	Basalt	0.537	1	within 200 feet	secondary
Mvc(1)	Volcaniclastics	11.645	1	within 200 feet	secondary
OEvba	Basalt flows	5.693	1	within 200 feet	secondary
OEvc	Volcaniclastics	7.476	1	within 200 feet	secondary
Qgog	Outwash gravel	13.84	1	within 200 feet	secondary
Ec(2pg)	Continental sandstor	7.433	2	within 200 feet	secondary
Qa	Alluvium	2.894	2	within 200 feet	secondary
Qap(wh)	Glacial drift	0.858	2	within 200 feet	secondary
Qapo(lh)	Outwash deposits	4.607	2	within 200 feet	secondary
Qls	Landslide deposits	1.867	2	within 200 feet	secondary
Em(2m)	Marine sedimentary	2.619	5	within 200 feet	secondary
Qgm	Glacial marine?	0.052	5	within 200 feet	secondary
Qgos	Outwash sand	0.119	5	within 200 feet	secondary
Qgp	Glacial drift	12.677	5	within 200 feet	secondary
Qgt	Glacial till	7.636	5	within 200 feet	secondary
		230.652			

APPENDIX E

Deschutes Mainstem Erosion Sites in 100-Year Floodplain by Geomorphic Area